INVESTIGATION ON COAL WASHERY WASTE WATER AND EFFLUENT TREATMENT

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BY

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CE-1970-M-BAN-INV

A Man would do nothing, if he waited
until he could do it so well that no
one would find fault with what he
has done.

<div align="right">Cardinal Newman</div>

CERTIFICATE

Certified that the work presented in this thesis entitled "Investigation on Coal Washery Wastewater and Effluent Treatment" by Shri Nripendra Nath Banerjee has been carried out under my supervision and has not been submitted elsewhere for a degree.

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ACKNOWLEDGEMENT

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INVESTIGATION ON COAL WASHERY WASTEWATER AND EFFLUENT TREATMENT

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A b s t r a c t

A study was undertaken to characterise the effluents from several coal washeries so as to be able to ascertain the present problem in terms of their discharge to inland surface waters. Presently used methods of coal washery wastewater treatment by settling ponds was not found to be highly effective. It was apparent that further treatment of coal washery wastewater and/or effluent was necessary to meet the discharge standards with an added advantage of higher recovery of good quality coal fines and possible inplant reuse of the treated effluent.

It was demonstrated that inorganic coagulants like alum or ferric chloride with or without polyelectrolytes as coagulant aids and polyelectrolytes as prime coagulants were effective in clarifying the effluent. Alternatively, the effluent or the wastewater (feed to the settling ponds) may be effectively treated by extended plain sedimentation. It was also shown that the efficiency of the thickener used in the closed circuit coal washing process may be improved by modifying the thickener operation and judicial coagulant addition.

1. INTRODUCTION

Recent energy crisis has led to increased worldwide production of coal. In India, the challenge is being met through mechanisation in mining and loading operations giving rise to increased ash content in coal. Also, the present higher demand of coal is rapidly depleting the reserves of good quality coking coal. In order to be able to supply good quality metallurgical coking coal under the present circumstances, the only economic solution is the coal washing. Consequently, a large number of coal washeries has been set up in the coal producing regions of the country. These washeries release their effluents high in suspended solids (coal fines) into the nearby bodies of water resulting in severe water pollution problems as well as loss of substantial amounts of good quality coal fines. The polluted river water becomes unsuitable for subsequent industrial and municipal uses. The downstream water works face serious problem in removing the suspended solids. Large quantities of suspended solids also hinder the movement and breathing of fish and the river becomes unsuitable for fish breeding. Thus, there is an urgent need to evaluate the presently used methods of coal washery wastewater treatment and to investigate new methods and/or modification of the existing practices.

The first objective of the present study was to characterise the effluents from several coal washeries to assess the severity of the problem. Using one of the washeries as a model, e.g.,

the Patherdih Coal Washery, the second objective was to evaluate
the efficiency of the settling ponds presently being used for
washery wastewater treatment as well as the potential of further
treatment of the effluent. A study was also undertaken to
investigate the operation of the thickener used in the closed
circuit coal washing process with a view to suggest possible
modification.

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2. COAL WASHERY

2.1. Coal Washing

2.1.1. General

With the spurting prices of mineral oil and imposed restrictions on its supply in recent years, coal now reigns supreme in the energy world. To meet the higher demands of coal in the years to come, all coal-rich countries including India have drawn up short and long term plans for enhanced output of coal through intensive mechanisation. But the mechanisation of mines coupled with the depletion of superior quality coals have led to appreciable deterioration in the quality of run-of-mine (r. o. m.) coal due to the introduction of extraneous dirt band from inside and/or outside the coal seams. These factors along with the increased industrial demand of high quality coals of low ash content have compelled the coal industries to incorporate coal washing as an adjunct to higher production of coal through mine mechanisation.

Irrespective of the techniques of washing, the principal operations involved in coal washing are the following (Sarkar,1977):

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      (i) Pretreatment of r.o.m.coal
     (ii) Coal washing or cleaning
          (a) Coarse coal washing
          (b) Small coal washing
          (c) Slurry beneficiation
    (iii) Dewatering and drying of wet products
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(i) Pretreatment of r.o.m. coal

Pretreatment of coal mainly consists of crushing or size reduction, blending, and storage of coal to ensure

uninterrupted and uniform feed for washing. Depending on the feed capacity and constrains due to environmental pollution abatement measures, open stock piles with Robin-Messiter blending system or concrete bunker silos with controlled blending devices are used for the purpose.

Sizing of r.o.m. coal prior to washing is generally achieved in two stages. For the size classification of coarse coal above 10 or 15 mm, dry screens are usually used whereas for the removal of fines below 1 or 0.5 mm, the general trend is to use desliming screens with controlled showers of water.

For effective treatment of moderately difficult washable coking coals as are found in India and Australia, the normal practice is to crush the r.o.m. coal directly to 35 or 15 mm before washing.

(ii) Coal washing or cleaning

Coal washing is mainly based on the differences in the physical properties between the coal and its impurities, particularly on the differences of specific gravities. The specific gravity of coal depends in some degree upon its intrinsic impurities and varies from 1.? to 1.5, a generally accepted value being 1.25. Most of the impurities present in coal are heavier than coal itself and the separation of coal from impurities can be achieved by an engineered us: of this difference. In practice, the main problem faced is to separate impure coal from more or less carbonaceous rocks and the arbitrary demarcation line is generally governed by economic considerations.

(a) Coarse coal washing

Air pulsater jigs or heavy media process are widely used for washing of coarse coal above 15, 10, or 6 mm size. In jigging, coal particles in a bed are subjected to upward current of water which causes the particles to stratify in such a manner that the lighter particles collect at the top and the heavier refuse particles settle at the bottom. The heavy media process is a straight forward flotation process. Separation of coal from impurities is achieved by using a fluid media (a suspension of sand or magnetite in water to the desired specific gravity) of specific gravity greater than that of the coal but less than that of the impurities. This allows the clean coal to float and the heavier impurities to sink, arrangements being made to collect the two phases separately.

For coals of drift origin as are found in India, heavy media processes are most common.

(b) Small coal washing

The common systems of small coal washing include air pulsated jigs (preferably employing feldspar bed), heavy media cyclones, Diester tables, etc. For coal with high near gravity materials at the desired density of cut as well as for low density separation, heavy media cyclones and Vorsyl centrifugal separators are most efficient.

(c) Slurry beneficiation

Froth flotation is the most widely accepted technique for the treatment of slurry forming fines, particularly when they

are of coking quality. The flotation feed is normally conditioned
in presence of both a frother and a collector to ensure higher
carboneceous material recovery. Commonly used collector is
similar to keresene and the frother is of alcohol family.

A special technique of coal flotation (oleoflotation)
developed and patented by the Central Fuel Research Institute,
Dhanbad (Chakraborty, et.al., Indian patent No.100675) uses
surface active oils and fixed screens followed by centrifuge
for dewatering of the slurry either alone or in admixture with
clean coal above 0.5 or 1.0 mm size. This integrated process
may be employed for simultaneous upgrading and dewatering of the
slurry.

(iii) Dewatering and drying of the wet products

Coal leaves most of the washing processes with a
high percentage of surface moisture which must be reduced before
use. Natural drainage on screens removes a large fraction of
the moisture from the larger size coal (plus 15 mm) which may
be dewatered easily in storage-cum-dewatering bunkers. Small
coal fractions (minus 15 mm) are normally dewatered in centrifuges.
Vacuum filters are commonly used for finer sizes such as those
upgraded by froth flotation while thermal dryers are used to
bring down the surface moisture of wet fines to the level of
5 to 6 percent.

2.1.2. Coal Washing In India

The average ash content of Indian coking coal is
rarely less than 24 percent. With the progressive introduction

of mechanisation both in mining and loading, the average ash
content is likely to rise further. As against this, the ash
content of metallurgical coal is normally specified to be in the
range of 15 to 17 percent depending on the volatile matter content
of the coking coal. Besides blending with appropriate low ash
coal, washing has to be resorted to for preparing feed to produce
metallurgical coke of desired quality.

Indian coals are believed to be of drift origin which
resulted in intimate mixing of mineral matter in the coal substances
As a result, such coals are very difficult to wash, and were one
time considered as practically non-washable. The problem has now
been tackled successfully on a commercial scale based mainly on
the coal preparation studies conducted by the Central Fuel Research
Institute, Dhanbad (Sarkar et.al., 1972). A list of washeries
which are now under operation in India for washing of coking and
semi-coking coals is presented in Table I.

Some of the special features of washing of Indian
coals are blending of raw feed, crushing of r.o.m. coal to smaller
sizes, prewashing of the crushed coal, and use of heavy media
washers and cyclones for different fractions of prewashed coal.
According to the general scheme of washing, Indian coal washeries
may be broadly classified into three groups:

(i) Group I - washeries designed to wash coal of easy or
medium cleaning characteristics. Fig. 1 illustrates the washing
scheme of this group. The washeries at Bhojudih, Durgapur (HSL),
Kargali and Gidi conform more or less to this generalised scheme.

Table 1. List of Coal Washeries

Washery	Raw Coal Input (million tonnes/yr)	Rated Capacity (tonnes/hr)
I. Coking Coal Washeries		
1. West Bokaro	0.70	135
2. Jamadoba	1.44	300
3. Kargali	2.72	650
4. Lodna	0.40	70
5. Durgapur (HSL)	1.50	360
6. Dugda I	2.40	600
7. Bhojudih	2.00	500
8. Patherdih	2.00	500
9. Chasnala	2.70	550
10. Durgapur (DPL)	1.35	300
11. Dugda II	2.40	600
12. Kathara	3.00	800
13. Sawang	1.00	250
II. Semi-coking Coal Washeries		
1. Gidi	2.84	800
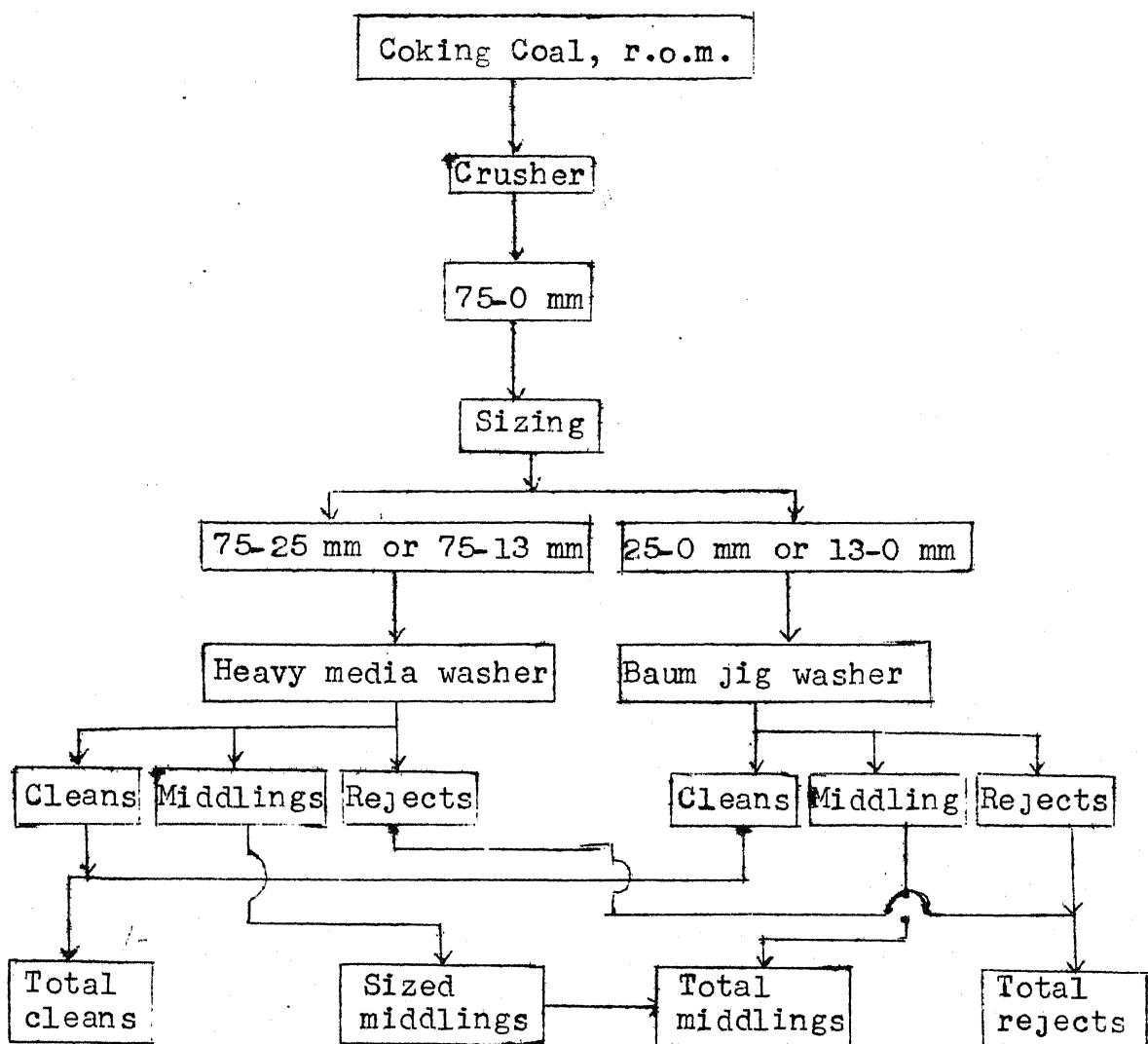
Fig. 1. Composite Washing Scheme for Coking
Coal (without prewashing)

(ii) Group II - washeries designed to wash mixed supplies of coals with fluctuations in cleaning characteristics. The washing scheme is illustrated in Fig.2. Both Dugda I and Patherdih washeries are under this group.

(iii) Group III - washeries scheduled to wash coal of difficult cleaning characteristics. The general washing scheme of this group is presented in Fig. 3. The washeries installed at Kathara, Sawang, Durgapur (DPL) and Dugda II belong to this group.

Coking coal, r. o. m.

↓

Crusher

↓

75-0 mm

↓

Prewashing in Baum jig

↓

Sizing

75-25 mm or 75-6 mm | 25-0 mm or 6-0 mm

↓ | ↓

Heavy media washer | Heavy media cyclone washer

Cleans | Middlings | Rejects | Cleans | Sinks (Rejects)

Total cleans | Total middlings | Total rejects
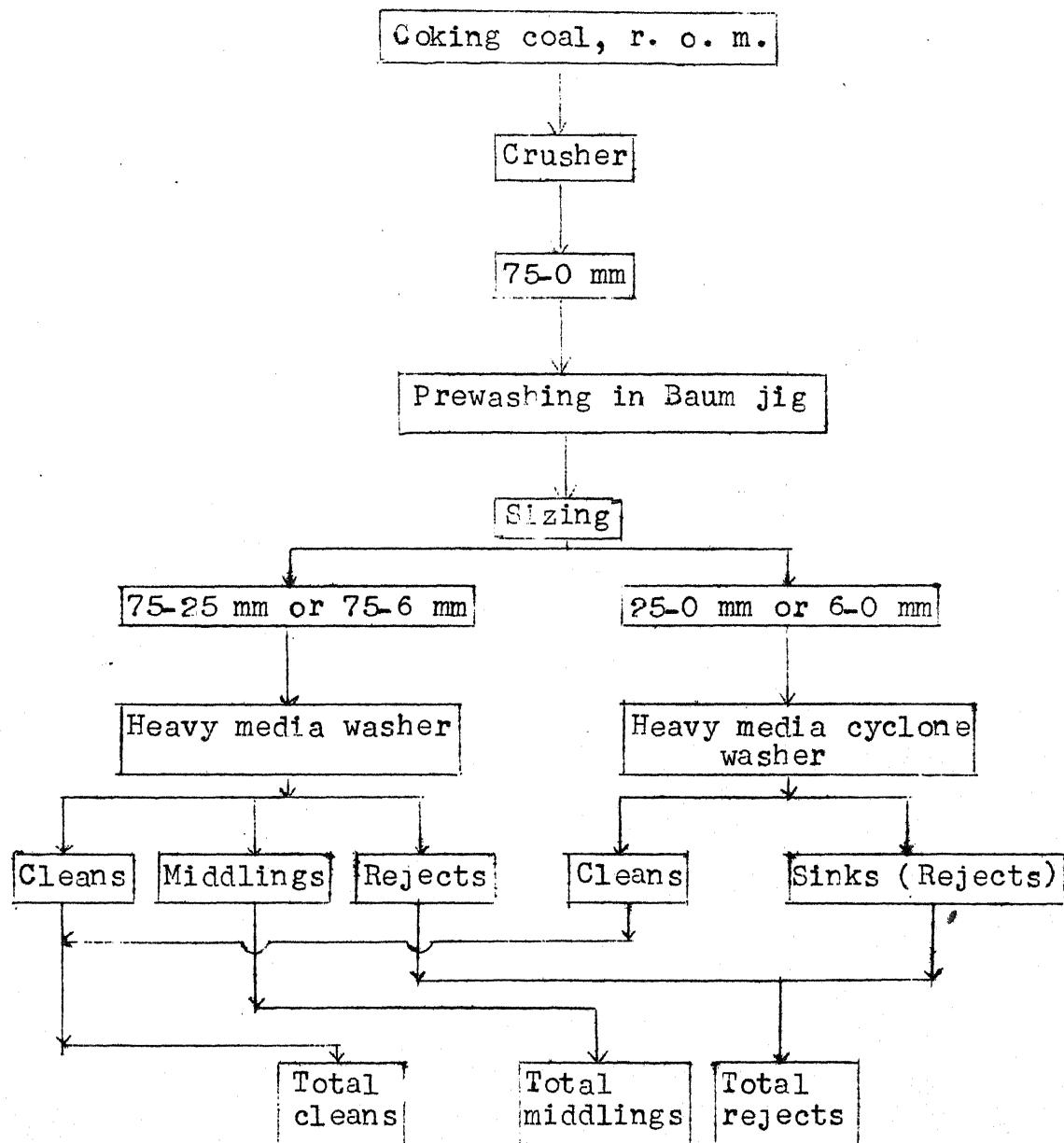
Fig. 2. Composite Washing Scheme for Coking Coal
(with prewashing)
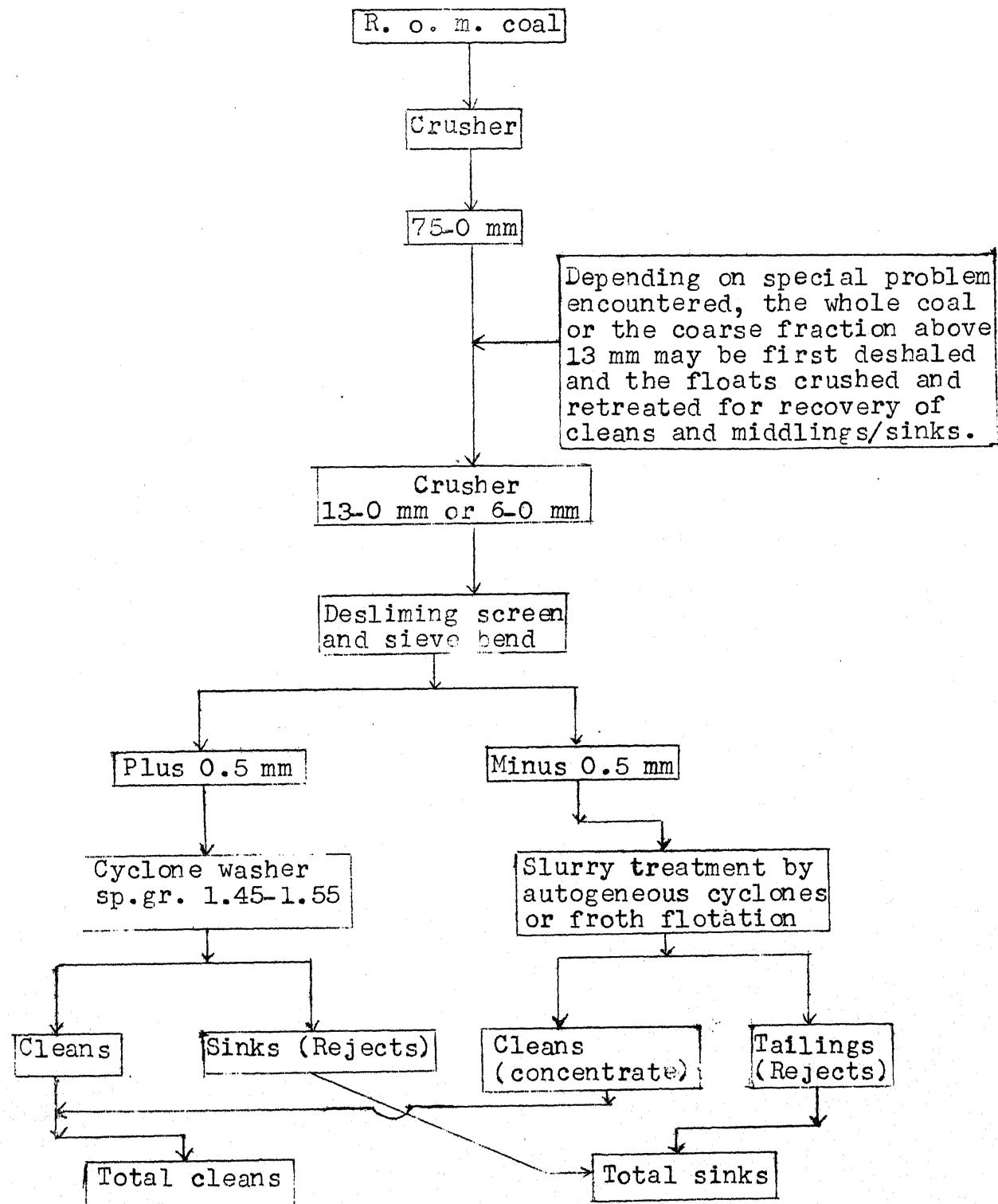
Fig.3. General Washing Scheme for Upgrading
of Inferior Coking Coal.

2.2. Coal Washery Wastewater

Formation of large quantities of slurry is inevitable in wet washing of coal and its amount depends on washability characteristics, method of mining, mode of handling, degree of crushing, and the scheme of washing. The amount of suspended solids in the slurry is always high with difficult washable coal which requires crushing to smaller sizes for effective washing. The coal in the slurry is to be separated from the mineral matter and recovered, and the clarified water should be recirculated for effective and economic operation of the washery.

The recovery of fines is generally by froth flotation and vacuum drying of the floated solids. The water in the effluent is clarified by settling the reject solids in settling ponds, often aided by chemical coagulants. In many plants where the ash content of the coal fines in the slurry is expected in the desired range for clean coal, the fines are recovered in a thickener followed by drying the thickened slurry in disc or vacuum filters. The overflow from the thickener is settled in settling ponds before discharging to streams. In some washeries, the overflow from the thickener is directly discharged to stream.

The effluent from the flotation unit or the overflow from the thickener(s) is defined in the present investigation as "coal washery wastewater." The effluent from the settling ponds treating either the flotation unit effluent or the thickener overflow is defined as the "coal washery effluent." In case of

washeries discharging the thickener overflow directly to streams
without any treatment, the wastewater and the effluent are
synonymous.

2.2.1. General Characteristics

The general characteristics of wastewaters from some
coal washeries are reported in Table 2. The data for Patherdih,
Bhojudih, and Dugda washeries are from analysis of wastewaters
from these washeries performed during the present investigation.
The data for Durgapur washeries were obtained through personal
communication (Dhaneshwar, 1976) and the characteristics of
wastewaters from the West Virginia washeries are from the
published work of Gillenwater (1951).

A sieve analysis of the solids in the Patherdih
washery wastewater is presented in Table 3. A sub-sieve range
(-300 BSS) analysis of the solids by sedimentation method is
shown in Table 4.

Analysis of the feed water used in Patherdih,
Bhojudih, and Dugda washeries are reported in Table 5.

2.2.2. Treatment and Present Problem

The primary objective for the treatment of coal
washery wastewater is the recovery and reuse of the large
quantity of water and the prevention of water pollution.
In case of washeries having no upgrading facilities for coal
fines such as flotation another important aspect of the treatment
is the recovery of large quantities of good quality coal fines.
As the coal washery effluent derived from the present method

Table 2. Characteristics of Coal Washery Wastewater

Washery	pH	Suspended solids (mg/l)	Dissolved solids (mg/l)	Hardness		Alkalinity	
				Ca as CaCO$_3$ (mg/l)	Mg as CaCO$_3$ (mg/l)	Phenol-phthalein (mg/l)	Methyl orange (mg/l)
Patherdih (22.3.77)	7.3	8,887	451	120.1	30.15	0.00	81.9
Bhojudih (25.4.77)	7.1	85,117	903	497.8	22.2	0.00	97.2
Dugda I & II (9.12.77)	7.2	11,240	450	151.3	62.5	0.00	95.3
Durgapur (DPL)	6.4	42,596	–	–	–	–	–
Durgapur (HSL)	8.0	3,382	–	–	–	–	–
West Virginia Washeries							
Plant I	7.65	54,188	2,436	1,560.0	–	-3.00*	66.0
Plant II	8.3	13,484	296	122.0	–	3.00	125.0
Plant III	8.4	123,584	427	30.0	–	1.50	180.0
Plant IV	7.7	95,746	397	390.0	–	-1.00*	45.5

*negative alkalinity denotes acidity.

Table 3. Analysis of Wastewater Solids of Patherdih Washery

Size Range (micrometer)	Percent by Weight
above 500	1.05
" 251	9.00
" 152	15.91
" 104	14.21
" 53	6.92
below 53	52.91

Table 4. Sub-sieve Range Analysis of Solids of Patherdih Washery Wastewater

Size (micrometer)	Percent by Weight
47.00 and above	46.31
33.00 and above	40.74
22.48 and above	36.65
19.98 and above	29.47
11.14 and above	12.15
7.60 and above	5.20

Table 5. Analysis of Washery Feed Water

Washery	pH	Suspended solids (mg/l)	Dissolved solids (mg/l)	Hardness		Alkalinity	
				Ca as CaCO$_3$ (mg/l)	Mg as CaCO$_3$ (mg/l)	Phenol-phthalein (mg/l)	Methyl orange (mg/l)
Patherdih	6.9	40	106	-	-	-	-
Dugda	7.1	428	140	-	-	-	-
Bhojudih	7.2	87	130	532	23	0.00	27.21

of treatment of the wastewater using settling ponds contain,
in almost every cases, large amounts of suspended solids
(Table 2) and a large volume of water is wasted, this needs
to be further treated for the recovery of the good quality
coal fines and possible reuse of the clarified water with
consequent prevention of river pollution.

Settling ponds provide the simplest means of treatment
of wastewater from washeries and is the most commonly used method.
Several other methods of treatment are also in practice. In one
method, the wastewater is pumped to abandoned sections of mines
and the solids are allowed to settle there. Another method
uses the treatment units such as filters, clarifiers, etc.
A settling pond is usually necessary with these types of treatment
(Gillenwater, 1951). In some washeries, the wastewater is pumped
to some properly excavated lagoons in the top of existing spoil heap
made from solid refuse of the plants. This method is effective
in removing suspended solids from the wastewater but the seepage
might still be undesirable due to leaching of various salts
from the refuse bed (Smith, 1968). Hummer (1965) has recommended
the pumping of the slurry to storage ponds or dams of sufficient
capacities and to allow the water to evaporate. Noone (1963)
suggested a method of concentrating the froth flotation effluent
in a thickener, filtering the thickened sludge, disposing off
the filtered solids and recirculating the thickener overflow and
the filtrate. An U.S. patent (Shubert, 1974) suggests the
clarification of washery wastewater in two stages. The coal

particles are recovered in the first step by agglomaration with heavy hydrocarbon oil and filtering the agglomarates as cake while in the second step the filtered water is freed from mineral matter by settling. Gieseke (1963) prefers flotation of coal fines and suggests coagulation of flotation effluents with synthetic coagulants for the recovery and reuse of water. Addition of coagulant is recommended by many authorities and appears to be in wide use in the treatment of slurry containing fines of coal washery (Bulovtskii and Pilyasov, 1962; Harper, 1960; Rozgaj, 1965; Kotkin and Rozhnova, 1962; Chattopadhyay, et.al., 1961; Chattopadhyay, et.al., 1964 and Rao and Sastry, 1968). An Indian patent No. 100795 of 1965 recommends the use of a patented coagulant "pherufloc" for the treatment of coal washery wastewater and claims that the coagulant is cheap, easy to operate, and removes over 98% of the suspended coal particles from the wastewater.

Most of the coal washeries in India are situated near the Damodar river and discharge their wastewaters or effluents to this river or its rivulets. Damodar river also receives the coal mine drainage, and the effluents from thermal power plants and chemical factories like the Fertilizer Corporation of India at Sindri, and has become one of the worst polluted rivers in the country (Das et. al., 1965). It has become so much polluted by the industrial effluents that it may now be called the industrial sewer of this area (Kumar and Vishwanatha, 1976).

Though the solids in coal washery wastewater or the effluent

do not have appreciable biochemical oxygen demand, these are

by no means less objectionable as water pollutants. The rivers

receiving such wastewater or effluent takes a black look due

to the deposition of coal fines and the water becomes unsuitable

for subsequent industrial and municipal uses. The down stream

water works face serious problems in settling and filtering the

coal fines from the water. Large quantities of suspended

solids also hinder the movement and breathing of fish and the

river becomes unsuitable for fish breeding (Pantulu, 1965 and

Gillenwater, 1951).

Provisions such as flotation unit for upgrading

of coal fines in the slurry has not been incorporated in most

of the Indian washeries on the assumption that the ash content

in slurry fines from such washeries would remain within the

desired ash level of clean coal. A thickener is employed

instead and the overflow is normally treated by settling in

sedimentation ponds, settled solids being sun dried and mixed

with clean coal. In a small number of washeries where upgrading

of coal fines is practised by flotation, the effluents from

the flotation unit are settled in sedimentation ponds and the

pond effluent is discharged to river. The wastewater from

some washeries are not treated at all and are directly discharged

to river. The characteristics of the effluent discharged to

river from some washeries are given in Table 6. It is seen that

the suspended solids content of the effluent is always more

Table 6. Characteristics of Coal Washery Effluent

Washery	pH	Suspended solids (mg/l)	Dissolved solids (mg/l)	Hardness		Alkalinity	
				Ca as $CaCO_3$ (mg/l)	Mg as $CaCO_3$ (mg/l)	Phenol-phthalein (mg/l)	Methyl orange (mg/l)
Patherdih 22.3.77	7.1	1,064	315	111.55	26.45	0.00	105.0
Patherdih 12.1.77	7.6	1,683	351	173.00 (total hardness)	-	-	-
Dugda	7.3	917	412	141.50	58.50	-	-
Bhojudih	7.3	922	808	398.20	16.80	2.6	144.0

than 100 mg/l, the specified upper limit of suspended solids for industrial effluents discharged into inland surface water (I S : 2490-1974).

3. SCOPE OF THE INVESTIGATION

It is evident from the preceding discussion that discharge of coal washery wastewater to rivers constitute a rather serious threat to environmental quality and reduces the potential of the water for immediate and subsequent beneficial uses. This is also the situation when the wastewater is subjected to treatment through settling ponds since such treatment as practised,also is not adequate to reduce the suspended solids content below a specified upper limit. Apparently, there exists a need to critically evaluate the efficiency of the presently used methods of coal washery wastewater treatment and to suggest necessary modification and/or incorporation of additional treatment units. The present investigation was directed towards this objective.

Patherdih coal washery was chosen as a model washery for conducting the present investigation. The process flowsheet and the water circulation scheme of the washery are presented in Fig. 4 and 5, respectively. Patherdih is a three product washery, the products being cleans, middlings and rejects. The washery incorporates Baum-jig for prewashing of minus 75 mm coal, heavy media washer for retreating 75-13 mm prewashed coal, and heavy media cyclones for treating 13-0.42 mm size fraction of prewashed coal. The fines in the slurry is thickened in a thickener using calcium chloride and Morarfloc A as coagulants, the thickened underflow is filtered in a disc
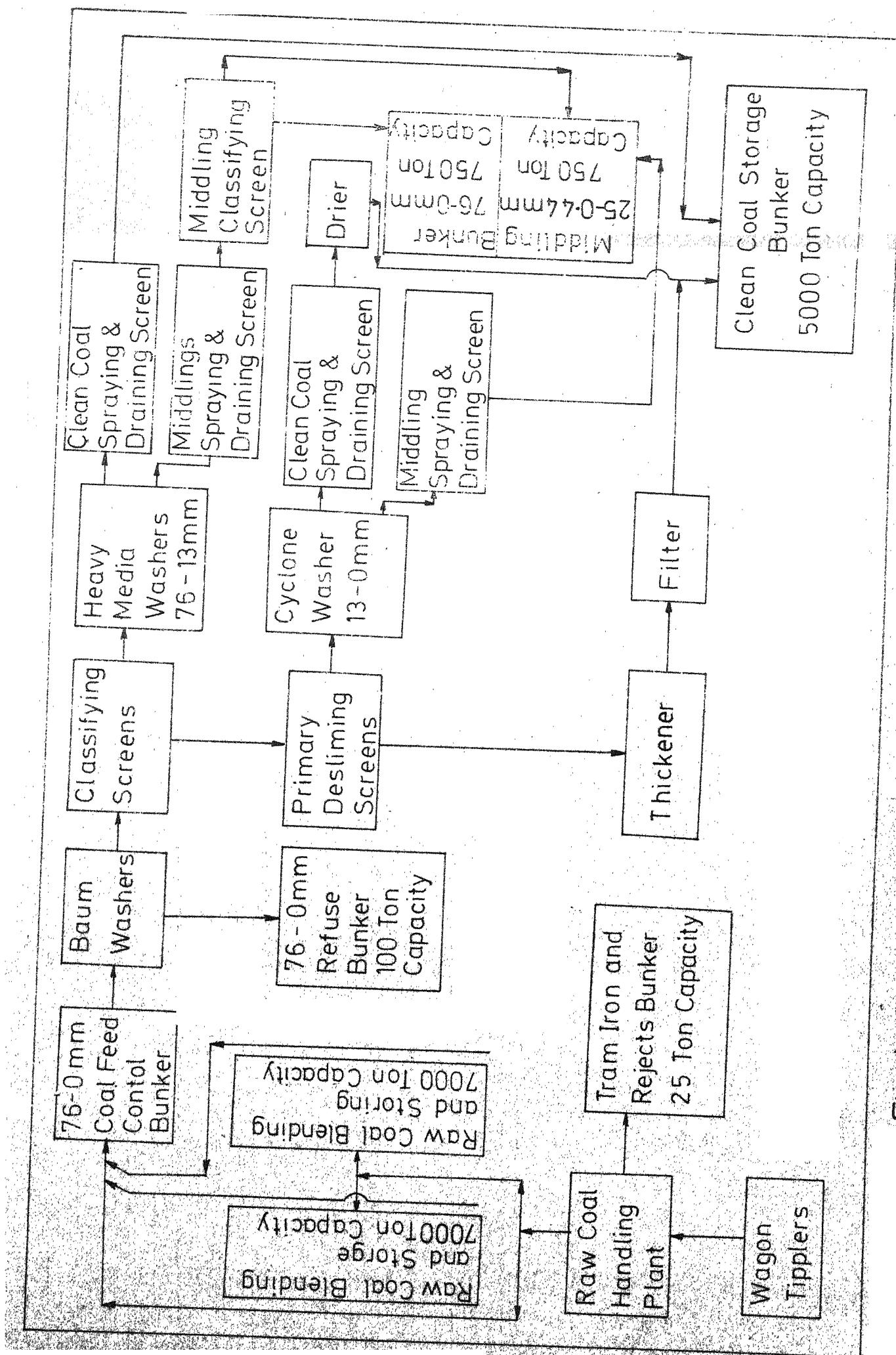
Fig. 4. Process Flowsheet for Patherdih Washery

With Rejects

Baum Washers

Classifying Screens

Heavy Media Washers

Clean Coal Spraying and Draining

Middlings Spraying and Draining

With Middlings

Primary Desliming Screens

Cyclone Washer

Clean Coal Spraying and Draining

Middlings Spraying and Draining

Drier

With Clean Coal

Coagulant

Thickener

Clean Coal Disc Filter

Clarified Water tank

Fresh Water Tank

Note: Washery spill water along with a portion of the thickener overflow are settled in an unlined pond for recovery of coal fines and the pond effluent is discharged into River Kadma

Fig.5. Patherdih Washery Water Recirculation Scheme

filter and the filter cake is mixed with the clean coal. Though
the washery was initially planned to run in a closed circuit,
a portion of the thickener overflow is almost regularly allowed
to bleed out of the circuit. The fines in the wastewater
comprising of the overflow and the spill water from different
units of the plant, is settled in open ponds and the pond
effluent is discharged to river Kadma, a tributary to river
Damodar. The wastewater is allowed to flow to a pond till the
solids fill up the pond almost completely and then the flow is
diverted to other ponds. The deposited solids are sun dried
and the dried material is mixed with clean coal.

The present study, using the Patherdih washery as
a model washery was undertaken along the following lines:

(a) evaluation of the efficiency of the settling ponds
presently being used for coal washery wastewater treatment, and

(b) further treatment of the present pond effluent by
chemical coagulation.

Extended plain sedimentation studies on the wastewater
and pond effluent were also undertaken to assess its potential
when adequate land may be available.

A study was also undertaken to assess the working
of the thickener used in the closed circuit coal washing process
with a view to suggest possible modification.

4. BACKGROUND OF THE METHODS OF INVESTIGATION

4.1. Sedimentation

In environmental engineering, the term sedimentation is applied to describe the gravity settling of suspended solids through a liquid, usually water. Particles settle out of a suspension in one or more of four different ways, depending on the concentration and the flocculating characteristics of the particles in the suspension (Fitch, 1958). The effects of these factors on the settling regime is indicated in Fig. 6.

Class 1 clarification refers to the settling of dilute suspension of particles which have little or no tendency to flocculate. Particles maintain their individuality and do not change in size, shape or density during settling. The removal of dilute suspension of flocculent particles is referred to as Class 2 clarification. In flocculent suspension of intermediate concentration, the particles are close enough to permit interparticle forces to hold them in a fixed position relative to one another. As a result, the particles settle as a mass and there is a distinct interface between the supernatant and the settling solids. This type of sedimentation is termed as zone settling (Class 3 clarification). When the particles actually contact each other, the weight of the particles is supported, in part, by the structure formed by the compacting mass and the resulting structure acts to restrict further consolidation. This action is called 'compression' (Class 4 clarification).
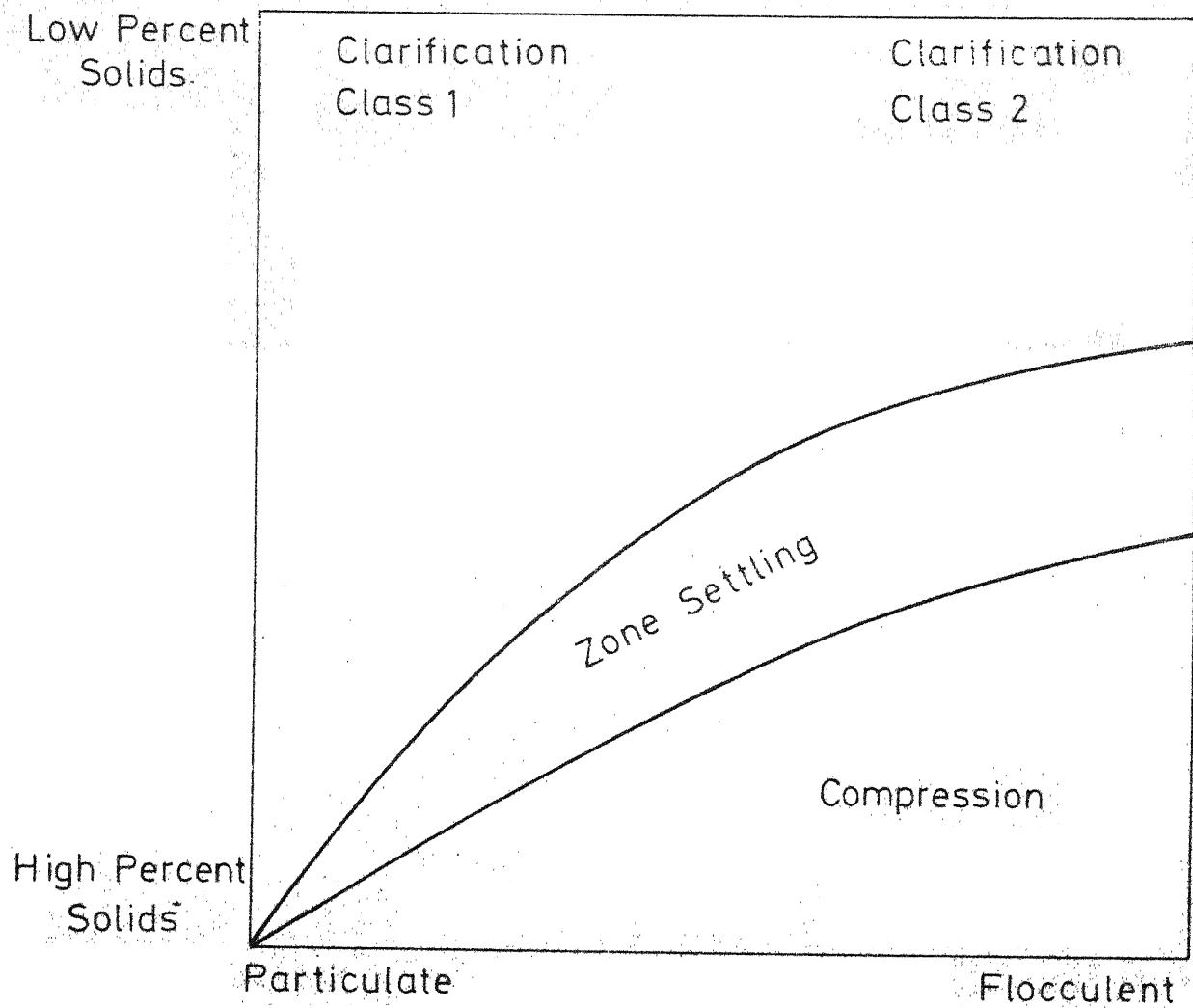
Fig. 6. Paragenesis Diagram

4.1.1.Column Settling for Class 2 Clarification

The settling of flocculent suspended solids in water and wastewater is shown in Fig. 7. As noted, the newly formed particle, after coalescence generally exhibits a greater settling velocity than the original two particles. For a discrete particle, the settling velocity remains same and the efficiency of removal depends only on the velocity or the over flow rate, whereas the removal efficiency for a flocculating particle is a function of both the clarification rate and the depth. In practice, the flocculation phenomenon is much more complex than shown in Fig. 7. Many particles are involved in the process and because of the hindered settling effects, the particles may be moving upward and downward prior to coalescence. The fluid shear forces may cause partial breakup of larger particles flocculated in the upper region of the basin. Thus it is not possible to predict the performance of a sedimentation tank for most water and wastewater applications from the theoretical consideration alone. Batch type column settling studies or continuous flow pilot plant studies are required for this purpose.

Camp (1946) suggested a batch type column test in which suspended solids concentration is established at various times and depths. Additional work and analysis of the technique were reported by Eckenfelder and O'Connor (1961), Rich (1961), Clark,et.al., (1971) and the Association of Environmental Engineering Professors (1972). The usual procedure is to place
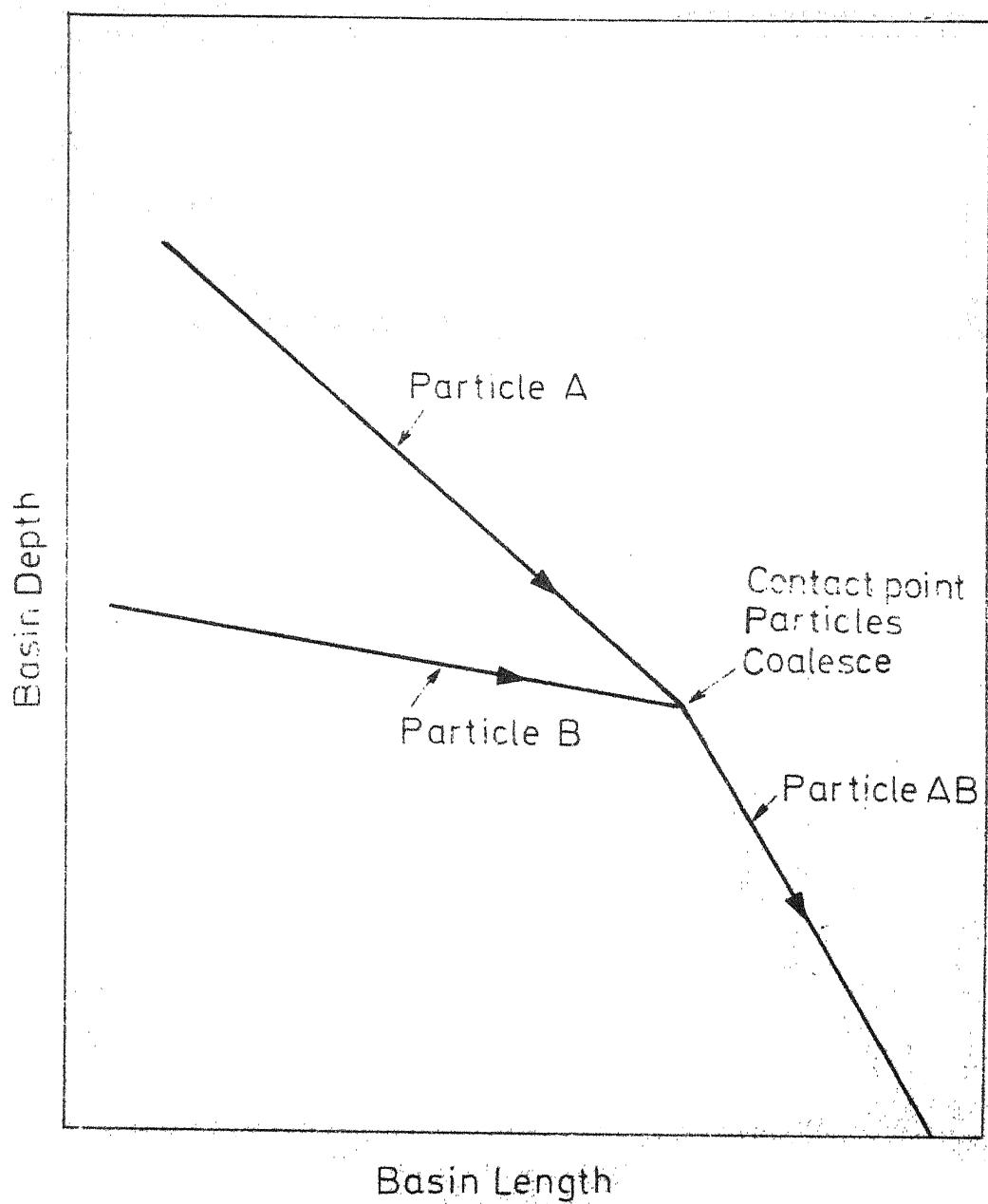
Fig. 7 Trajectories of Two Settling Particles
That Flocculate in Horizontal Flow —
Through Basin (Zanoni and Blomquist,
1975)

the sample in a 6-8 ft long column with taps for removal of samples at different depths. A series of samples is removed from the taps four to six times during the test period. The suspended solids concentration of each of the sample is determined and knowing the initial concentration of original sample, percentage removal of solids for each time and depth is calculated. The percentage removal data are then plotted at the appropriate depth and time and lines of isopercentage removal are approximated as shown in Fig. 8. The isopercentage lines are curvilinear for flocculent type suspension (linear isopercentage lines indicate the discreate nature of the suspended solids).

The isopercentage lines describe a depth-time ratio equal to the minimum average settling velocity of the fraction of particles indicated. For example, in Fig. 8, X_d of the particles in the suspension have had an average velocity Z_2/t_2 by the time the depth of Z_2 is reached. The same fraction of particles have had an average velocity Z_4/t_3 or greater by the time the depth Z_4 is reached. The overall removal in basin of depth Z_5 and at a clarification rate $q_0 = (Z_5/t_2)A$, where A = area of basin, is computed in the following manner. From Fig. 8 it is seen that, during the time interval t_2, X_c of the particles have had an average settling velocity Z_5/t_2 or greater. Of the remainder, X_d-X_c have had an average velocity Z'/t_2 and X_e-X_d an average velocity of Z''/t_2. Thus, the overall removal would be approximately:

$$X_T = X_c + \frac{Z'}{Z_5}(X_d-X_c) + \frac{Z''}{Z_5}(X_e-X_d) + \ldots\ldots\ldots$$
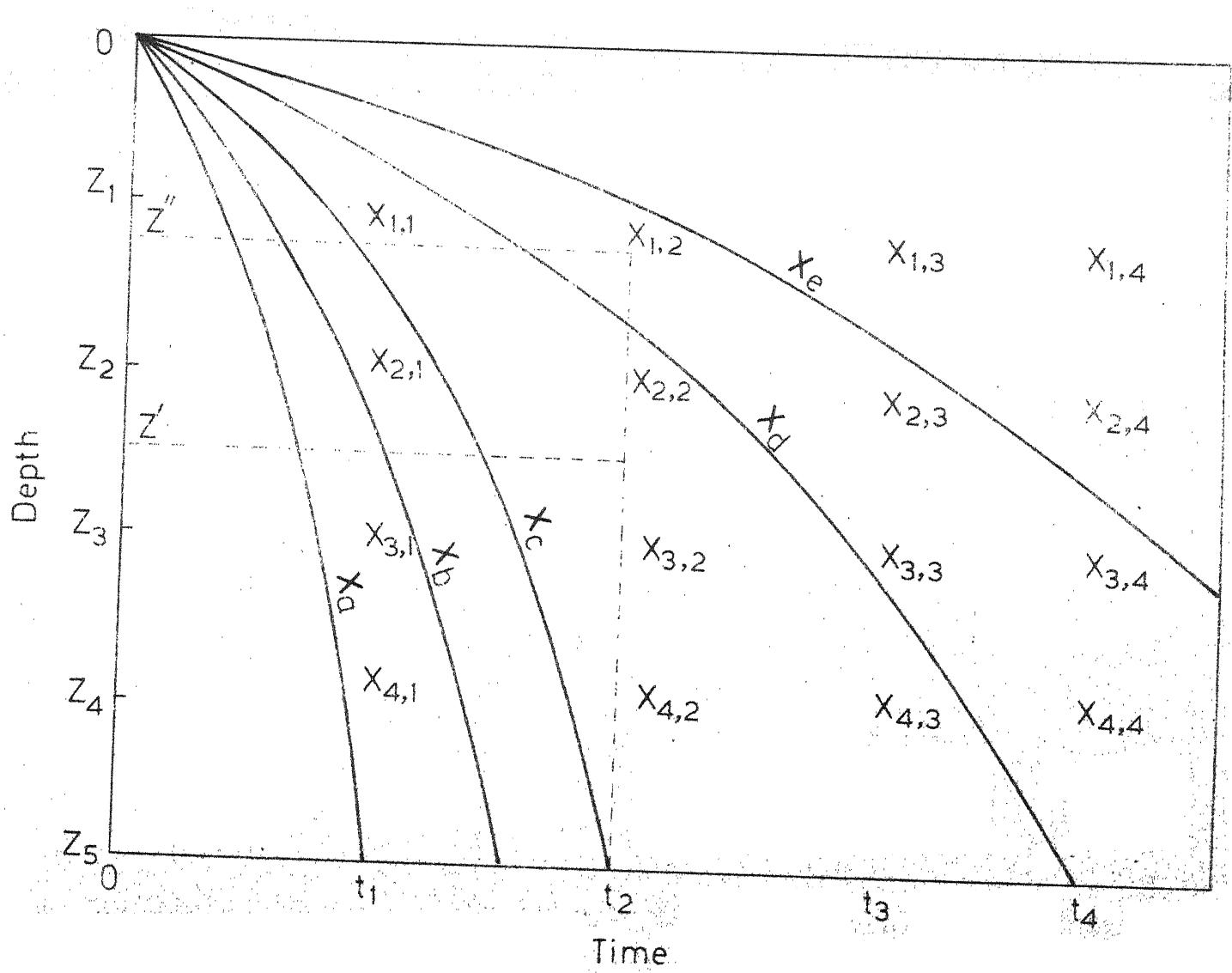
Fig. 8. Fractional Removal of Flocculating Particles as a Function of Time and Depth (Rich, 1961)

Removal in basins of other depths and rates of clarification can
be computed in a similar manner.

4.1.2. Zone Settling

Zone settling occurs in systems containing intermediate
concentration of suspended particles where the particles form a mass
which settles as a blanket with a distinct interface between
the settling sludge and the clarified zone. The settling
phenomenon that occurs when a concentrated suspension, initially
of uniform concentration throughout, is placed in a cylinder is
shown in Fig. 9. Initial height of the interface is h_o. In the
region from A to B there is a hindered settling of the particle-
liquid interface at a constant rate. The region from B to C
represents a transition into compression zone where deceleration
occurs. The region from C to D represents the compression zone
where the solids are supported mechanically by those beneath them.

For continuous flow sedimentation or thickening tanks,
the surface area required to separate concentrated suspension is
based primarily on two factors, viz., clarification capacity and
thickening capacity. Both the factors can be estimated from
batch settling tests. The clarification capacity of a system
can be estimated from the initial rate at which the interface
subsides. The required overflow rate for clarification must
be less than the zero settling velocity of the suspension. The
area required for clarification is given by:

$$A = \frac{Q}{v_s}$$
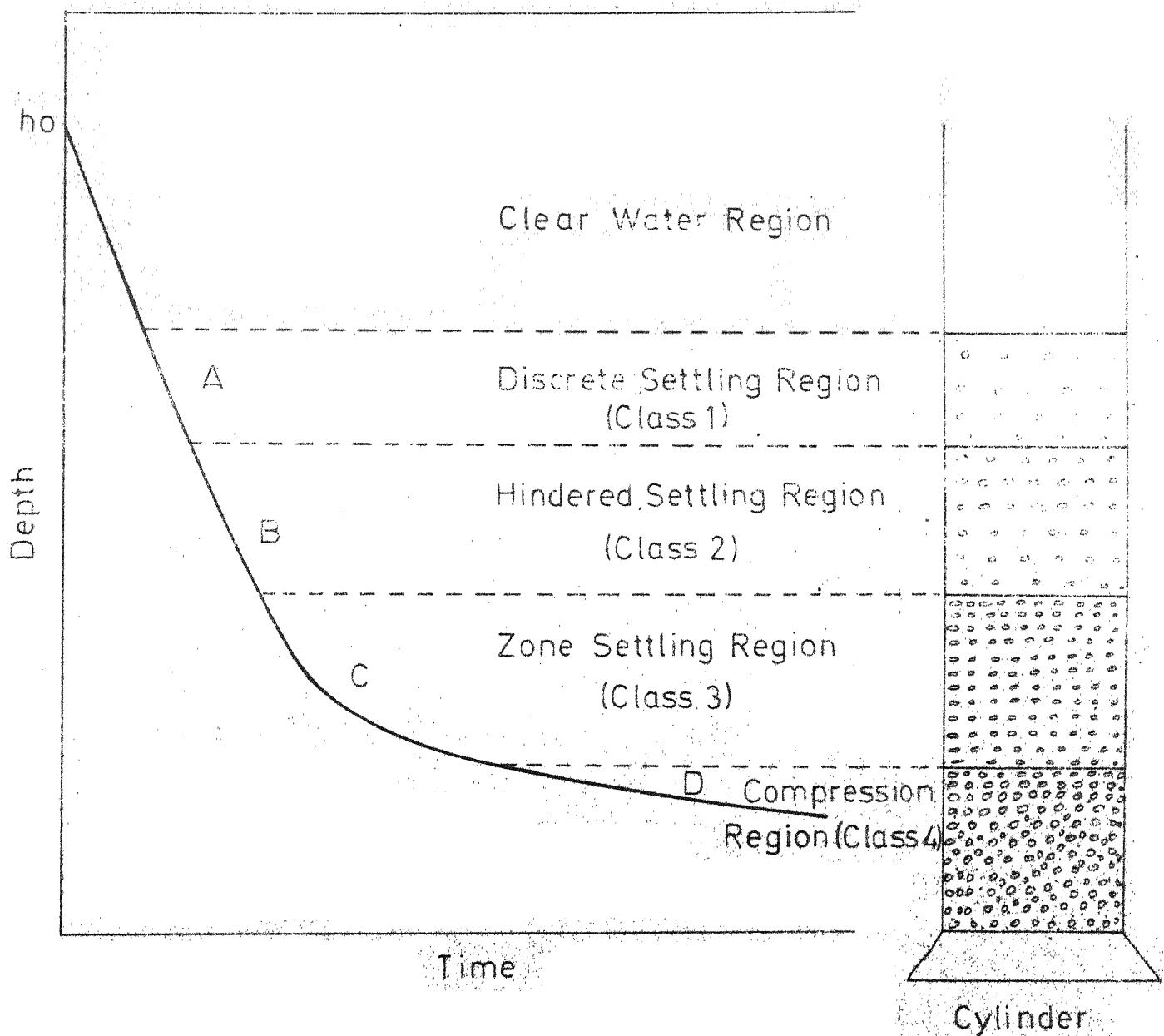
Fig. 9. Height of Interface and Settling Regions

where, A = surface area of the tank;

Q = rate of flow through the tank; and

v_s = subsidence velocity for hindered settling.

The value of v_s can be calculated from the hindered settling

portion (region A to B in Fig. 9) of the interface height versus

time curve.

The thickening capacity is determined by considering

the batch sedimentation characteristics of the suspension (Talmadge

and Fitch, 1955). The thickening area required can be calculated

from:

$$A = \frac{Qt_u}{h_o}$$

where, t_u = the time required to reach a desired sludge conentration

C_u determined from batch settling tests;

h_o = initial height of the interface; and

A and Q are as previously defined.

In zone settling design, the required area of thickening is a

function of the desired underflow concentration, C_u. There is

a critical concentration which will result in a maximum area

requirement and this should be the basis of design. Eckenfelder

and Milbinger (1957) estimated this critical concentration, C_c,

by bisecting the tangents to the hindered settling (region

A to B) and compression portions (region C to D) of the interface

height versus time curve as illustrated in Fig. 10. The point

at which the bisector intersects the curve represents the critical

concentration, C_c. The time t_u can be determined as follows:
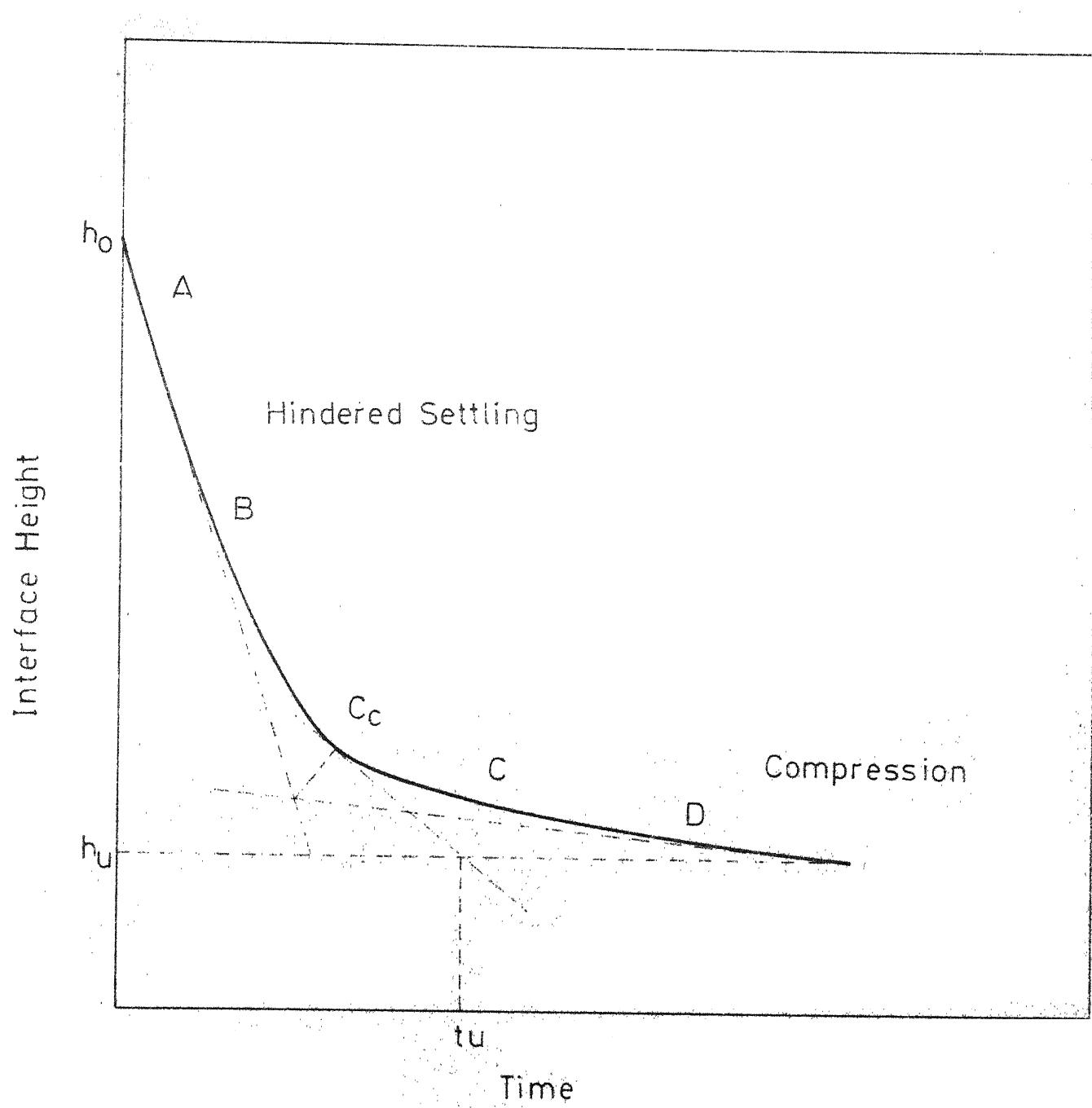
Fig.10. Interface Height Versus Time Curve for Zone Settling

(a) Construct a horizontal line at the depth h_u that corresponds to the depth at which all the solids are at the desired underflow concentration C_u. Thus

$$h_u = \frac{C_o h_o}{C_u}$$

where, C_o = initial concentration of the suspended solids; and

h_o, h_u and C_u are as defined earlier.

(b) Construct a tangent to the settling curve at the point of critical concentration, C_c.

(c) Construct a vertical line from the point of inter-section of these two lines to the time axis to determine t_u.

4.1.3. Extended Plain Sedimentation

A recent study by Yao (1975) demonstrated the potential of extended plain sedimentation based on both theoretical and laboratory investigations. Experimental results indicated the technical feasibility of the process to reduce a substantial amount of turbidity of waters laden with suspended solids.

Apart from advection due to fluid flow, the most important particle transport mechanisms in plain sedimentation are gravitational settling and diffusion. The relative significance of the two mechanisms to a given suspended particle depends largely on its size. Diffusion can be dominating when the particle size is small. It can be shown that the ratio of the displacement of a suspended particle in a given time period due to diffusion to that due to gravitational settling is as

follows (Streeter, 1962 and Wax, 1954):

$$\frac{x_d}{x_g} = \frac{8.29}{s_s-s} \left(\frac{kT\,\mu}{t}\right)^{0.5} \frac{1}{d^{2.5}}$$

where, x_d = displacement of the suspended particle during time

t due to diffusion;

x_g = displacement of the suspended particle during time

t due to gravitational settling;

s_s = specific gravity of the suspended particle;

s = specific gravity of water;

k = Boltzmann constant;

T = absolute temperature;

μ = dynamic viscosity of water; and

d = particle diameter.

The relative significance of the two mechanisms varies with particle size as well as the settling period. The longer the period, the less pronounced will be the diffusion effect for a given particle sizes. This is probably due to the random nature of the Brownian movement as compared with the unidirectional gravitational settling. The effect of diffusion decreases rapidly with the increase of particle size. If a difference of two order of magnitude or more between x_d and x_g is considered to be sufficient to ignore the significance of the lesser one, the limiting particle sizes with gravitational settling dominating will be about 1.4 μm for t = 1hr, 0.5 μm for t = 5 days and 0.4 μm for t = 20 days. These values indicate the practical limit of the removal of suspended particles that can be

attained by gravitational settling. Stokes law is normally
used to describe gravitational settling of discreate particles
and is given by:

$$U = \frac{g}{18} \frac{d^2}{/u} (s_s - s)$$

where, U = settling velocity of a suspended particle which is

　　　　another form of the design parameter overflow rate; and

　　　　other symbols as already described.

It has generally been recognised that detention time is not a major
factor in settling tank design. A deeper tank merely increases the
detention time without achieving functional improvements. Thus,
to be more appropriate, the term extended plain sedimentation
should be interpreted as extension towards a lower design overflow
rate as compared with those used in conventional plants rather
than as extension in detention time (Yao, 1975).

4.2. Coagulation in Water and Wastewater Treatment

　　　　Impurities in water and wastewater vary in size from
a few Angstroms for soluble substances to a few hundred micrometers
for suspended solids. The removal of a large proportion of these
impurities in water and wastewater treatment is accomplished by
sedimentation. However, because many of the impurities are too
small for gravitational settling alone to be an effective removal
process, the aggregation of these particles into large, more
readily settleable aggregates is essential for successful removal
by sedimentation. This process of aggregation is termed
coagulation.

The terms 'coagulation' and 'flocculation' are often used in literature with some different interpretations. LaMer (1964) used the term 'coagulation' to refer to destabilisation produced by compression of the electrical double layer surrounding all colloidal particles, and the term 'flocculation' to refer destabilisation by adsorption of large organic polymers and the subsequent formation of particle-polymer-particle bridge. He has used the terms to distinguish between the two modes of particle destabilisation but does not consider modes of particle transport. Weber (1972) used the term 'coagulation' to refer to the overall process of particle aggregation including both destabilisation and transport and the term 'flocculation' to refer to transport only. Thus 'flocculation' has been defined as a part of coagulation and this terminology has been used in the present discussion.

According to the Manual of Water Supply and Treatment (1976):

> "coagulation describes the effect produced by the addition of a chemical to a colloid dispersion, resulting in particle destibi-lisation. Operationally, this is achieved by the addition of appropriate chemical and rapid and intense mixing for obtaining uniform dispersion of the chemical. Flocculation is the second stage of the formation of settleable particles (or flocs) from destabilised colloidal sized particles and is achieved by gentle and prolonged mixing."

Coagulation is used in both water and wastewater treatment and the success of subsequent treatment processes depends on successful coagulation and sedimentation of the

suspended and colloidal particles. Coagulation is influenced by various physical and chemical parameters like the electrical charges on the particles, particle sizes and concentrations, pH, temperature, and the type and dosages of coagulants and coagulant aids. Coagulation processes can not be designed on the basis of theories from the field of colloid chemistry and fluid mechanics alone. Extensive laboratory studies are required to find out the optimum conditions to be adopted for the success of the process. This, however, does not decrease the value of applying sound theory in practice. Theoretical considerations help in the design of experiments and to interpret scientifically the results of such experiments.

4.2.1. Mechanism of Coagulation

Theories as to the nature of the interaction of the coagulants with various colloidal impurities have changed over the years from the early concept of simple enmeshment of colloidal particles by geletinous hydroxides, to the invocation of Schulze-Hardy rule, to emphasize upon the properties of hydrolysis products and then to specific chemical interactions and various adsorption models. Two different approaches have been advanced from time to time to explain the basic mechanisms involved in the stability and instability of colloid system:

(i) The physical or double layer theory emphasizes the importance of the electrical double layers surrounding the

colloidal particles in a solution and the effect of counterion adsorption and zeta potential reduction in the destabilisation of the system.

(ii) The so called chemical theory assumes that colloids are aggregates of definite chemical structural units and emphasizes specific chemical interaction between the coagulant and the colloids.

These two theories may appear contradictory but they are not mutually exclusive. Both mechanisms must be employed in a comprehensive understanding and in effective control of colloid stability and instability.

(i) Physical Theory

An important factor in the stability of colloids is the presence of surface charges on the colloid particles. The origin of these charges is due either to the adsorption of ions from solution or from the dissociation of ionisable groups present in the colloids. It is now almost certain that both causes operate simultaneously in most cases, one or the other predominating with different types of colloids. It is also clear that the charges on the colloid particles are compensated by equal and opposite charges (ionic) in the liquid in immediate contact with it, the system as a whole being electrically neutral. The whole system of charged colloid particles plus the oppositly charged ions in the dispersion media, referred as 'counterions' constitute an

electrical double layer. The classical theory of Helmholtz
assumes the double layer to be compact, there being abrupt
potential gradient between the two phases. This concept was
later modified by introducing the concept of diffused double
layer (Gouy, 1910), to which Poisson's equation was applied to
find the equilibrium distance of ions in the double layer
(Chapman, 1913). Finally, an electrical double layer was
proposed which combines Gouy-Chapman diffused layer and
Helmhotz fixed layer (Stern, 1924). In this Stern-Gouy diffuse
double layer model, part of the counter ions remain in a
compact Stern layer on the charged colloidal surface as a
result of strong electro-static forces (repulsive) as well as
van der Waals forces (attractive) while the other part of the
counter ions extend into the bulk of the solution and constitute
the so called diffuse Gouy-Chapman layer. The effective
thickness of this Stern-Gouy double layer is influenced
greatly by the overall ionic concentration of the solution
but relatively little by the size of the colloids. The
potential at the plain of the shear, i.e., at the surface
enclosing the fixed layer of ions attached to the colloid
particle is defined as zeta potential. Coagulation of colloid
particles is considered to be due to the reduction of this
zeta potential (repulsive force) well below van der Waals forces
(attractive). Depending on the characteristics of the
different types of counter ions involved in colloidal system,

this reduction may be attained by (a) compression of the
double layer thickness due to the incorporation of simple
counter ions in the diffuse double layer, and (b) by the
specific adsorption of counter ions onto the particle surface
with a concurrent reduction of the surface potential of the
colloid particle.

(a) Double layer compression: Coagulation with simple
non-hydrolysed ions like Na^+, Ca^{++}, etc. is due to this double
layer compression mechanism. High concentration of the
electrolytes in the solution results in corresponding high
concentration of counterions in the diffuse layer and the
thickness of the diffuse layer is reduced because of the
increased attraction between the positive and the negative
charges. The interactions of these coagulants, termed as
indifferent electrolytes, with a colloidal particle are
purely electrostatic and has been summarised by Hardy in
Schulze-Hardy rule which states that the destabilisation of
a colloid by an indifferent electrolyte is brought about by
ions carrying opposite charge to that of the colloid and
the coagulating action of these ions increases markedly
with the increase of the charge they carry.

(b) Adsorption and charge neutralisation: Coagulants
in natural systems are generally not indifferent electrolytes
and undergo many interactions in addition to electrostatic
attraction and repulsion. The ability of a coagulant to

destabilise a colloid dispersion is a composite of coagulant-
colloid, coagulant-solvent and colloid-solvent interactions.
Depending on the type and the magnitude of these reactions,
the ability of a coagulant to cause the deatabilisation of
a colloid dispersion may be considerably different from that
suggested by the double layer compression mechanism.
Tamamushi and Tamaki (1959) have reported that dodecylammonium
ions, a cationic polyelectrolyte, may be effectively used to
coagulate a negatively charged silver iodide sol. The
polycation has a charge of +1 and on the basis of double
layer compression mechanism, should exhibit an ability
to induce coagulation similar to that produced by Na^+.
However, the polycation produces destabilisation at a much
lower dosage and while it is not possible to overdose a
colloidal dispersion with Na^+, dodecylammonium ions produces
restabilisation of the colloids accompanied by charge
reversal. Similar results have been reported with respect
to adsorption and destabilisation/restabilisation phenomenon
effected by polydiallyl-dimethylammonium polycation and Ca^{++}
in suspension of manganese dioxide (Posselt, Reidies and
Weber, 1968 and Posselt, Anderson and Weber, 1968). It
was observed that destabilisation of colloids occurred as
a result of sorption of the polycation. Calcium ions also
effected destabilisation but at a higher dosage and did not
produce restabilisation. The polycation, on the other hand,
produced restabilisation of the colloids at a higher dosage

and this was accompanied with the reversal of charges. The charge reversal and the restabilisation of the colloids is due to the adsorption of excess counterions on the surface of the colloidal particles. It seems reasonable that coagulant-solvent interaction is at least partly responsible for the adsorption of the coagulant at the particle-solution interfaces. Cationic polyelectrolytes are surface active agents and these ions are squeezed out of water at an available interface because of the lack of interaction between the water molecule and the hydrophobic groups in the tails of these ions.

Another illustration of the effect of adsorption of counter ions and charge neutralisation is the coagulation of colloids by polyvalent metal salts like those of aluminium and iron. Matijevic, Janauer and Kerker (1964) have reported that coagulation with aluminium salts can be effective in low dosages, restabilisation accompanied with charge reversal occurs at higher dosages and coagulation is again attained with a still higher dosage of the salt. These have been explained by postulating that one or more of the hydrolysis products of the polyvalent metal ion may be responsible for the observed behaviour of the colloidal particles. When a quantity of Al(III) or Fe(III) salt, sufficient to exceed the solubility limit of the metal hydroxide, is added to water a series of hydrolytic reactions occurs proceeding from the production of simple hydroxo complexes (e.g., $Al(OH)_2^+$

Fe(OH)$_2^+$)through the formation of hydroxometal polymers to the formation of a metal hydroxide precipitate (Stumm and Morgan, 1962). These hydroxometal polymers are readily adsorbed at the colloidal interfaces (Matijevic et.al.,1961 and O'Melia and Stumm, 1967); simple aquometal ions are not adsorbed. Stumm and O'Melia (1968) concluded from their studies of colloid destabilisation by polyvalent metal salts that the destabilisation is accompanied by the adsorption of the hydroxometal complex polymers formed as kinetic intermediates during the transition to the precipitation of the metal hydroxide. The amount of the polymer adsorbed and consequently the dosage of the coagulant necessary to bring about the destabilisation, normally depends upon the colloid concentration and the dependence of this type has been loosely described by them as a stoichiometric relation of a coagulant dosage upon the colloid concentration.

Packham (1965) has shown that with an increase of turbidity in natural water, the coagulant dosage decreases. Stumm and O'Melia (1968) offered a possible explanation of this by stating that the required coagulant dosage depends on how the destabilisation is achieved. Destabilisation by adsorption of hydroxometal complex polymers requires a lower coagulant dosage which increases with the increase of the colloid concentration in the solution. Here the mechanism of colloid destabilisation is through adsorption of charged polymers and consequent charge neutralisation. The

destabiliation of high concentration of colloids is through
enmeshment of the colloids in the voluminous precipitates
of the metal hydroxide and the dosages tend to decrease as
the colloid concentration increases.

(ii) Chemical Theory

(a) Enmeshment in a precipitate

When a metal salt such as $Al_2(SO_4)_3$ or $FeCl_3$ or
metal oxide or hydroxide as in case of lime is used as
coagulant in a concentration sufficiently high to cause rapid
precipitation of a metal hydroxide (e.g., $Al(OH)_3$, $Fe(OH)_3$,
$Mg(OH)_2$)or a metal carbonate ($CaCO_3$), colloidal particles can
be enmeshed in these precipitates as they are formed
(Pachman, 1965). The rate of precipitation depends on the
extent of oversaturation and the concentration of the colloids.
For polyvalent metal salts, the rate of precipitation is also
influenced by the presence of anions in solutions if the
pH of the solution is in neutral or acid range; sulfate
ions being particularly effective (Miller, 1954). There
is an inverse relationship between the optimum coagulant
dosage and the concentration of the colloids in solution.

(b) Interparticle bridging

It is often observed that anionic polyelectrolytes
can be used as destabilising agents in the treatment of water
and wastewater though the solids in the water are also
negatively charged. This can not be explained on a simple

electrostatic model. LaMer and Healy, (1963), Michaels, (1954),

and Ruchrwein and Ward, (1952) have developed a bridging

theory which provides an acceptable qualitative model for

the ability of polyelectrolytes to destabilise colloidal

dispersions. A polyelectrolyte molecule to be effective in

destabilisation, must contain groups which can interact with

sites on the colloid particles. When a polymer molecule

comes into contact with a colloidal particle, some of these

groups are adsorbed at the particle surface leaving the

remainder of the molecule extending out into the solution.

If a second particle with some vacant sites comes in contact

with these extended segments attachment may occur thus

forming a particle-polymer-particle complex in which the

polymer acts as a bridge. If a second particle is not

available, the extended segment may eventually be adsorbed

on the other sites of the original particle and the polymer

is no longer capable of acting as bridge. Black, Birkner

and Morgan (1965) have shown that anionic polyelectrolytes

induce coagulation at lower concentration than aluminium

salts and restabilisation of colloids occur by overdosing

the system with the polyelectrolyte. This restabilisation

can not be ascribed to charge reversal since both the

polymer and the colloid have a similar charge. The

restabilisation is due to the saturation of colloid surfaces

by overdoses of the polymer since no sites on the colloids

are then available for the formation of interparticle

bridges (LaMer and Healy, 1963). Under certain conditions, a system which has been destabilised can be restabilised again by extended agitation, due to the breaking of the particle-polymer-particle bridge and the subsequent folding back of the extended segments onto the surface of the original particle.

Another mode of action of polyelectrolytes may be termed as coagulation-bridging phenomenon, which results from using extremely high molecular weight cationic polyelectrolytes. Besides acting as bridges between particles, these polymers also lowers the charge of the colloid particles through their adsorption on the colloid surfaces.

4.2.2. Alum and Iron Salts as Prime Coagulants

Alum and ferric salts are most commonly used coagulants in water and wastewater treatment. Both the coagulants have certain specific advantages. Selection of either of the salts is largely dependent on the suitability of the particular salt as coagulant for the water or the wastewater to be treated. Alum does not cause the unsightly red brown staining of floors, walls and equipment which may result when iron salts are used; nor is its solution as corrosive as the ferric salts. The dissolving of ferric sulfate also offers difficulties not encountered with alum. Aluminium ion is not reduced to more divalent form, as may be the case with ferric salts in waters high in organic matters. On the other hand, ferric floc is denser than

alum floc and is more completely precipitated over a higher
and lower pH range.

As discussed earlier, the destabilisation of
colloids by aluminium or ferric salts is brought about either
by enmeshment of colloids in hydroxide precipitates or by
adsorption of polymeric hydroxometal complexes. Destabilisa-
tion of colloids by the later mechanism is primarily influenced
by the coagulant dosage, pH and colloid concentration of the
water. Coagulant dosage and the alkalinity of the water
influence the resulting pH of the system because of the acidic
character of alum or ferric salts.

The interrelationship between the optimum coagulant
dosage, pH and colloid concentration and their influences on
the modes of destabilisation of colloids with aluminium or
ferric salts may be understood from the following. Four types
of suspensions may be encountered in water or wastewater
treatment:

(i) High Colloid Concentration and Low Alkalinity

Destabilisation is achieved in this case by
adsorpition of positively charged hydroxometal polymers which
are produced at acidic pH levels (pH 4-6 depending on the
coagulant). Colloid concentration being high, restabilisation
of colloids by overdosing of coagulant is prevented. In
such systems it is useful to lower the alkalinity of the
water (e.g., by elutriation of sludge) so that a strong
acid as that produced from ferric or aluminium salt can
depress the pH.

(ii) High Colloid Concentration and High Alkalinity

Destabilisation is achieved in such cases by adsorption and charge neutralisation at neutral and acid pH range. This may be brought about by using a high coagulant dosage (due to the high alkalinity the pH will generally remain in the neutral region where hydroxometal polymers are not highly charged so that charge neutralisation is difficult) or by elutriation to reduce alkalinity and using a lower dosage of coagulant at lower pH.

(iii) Low Colloid Concentration and High Alkalinity

Coagulation is readily accomplished here with a relatively high coagulant dosage through enmeshment of colloidal particles in a 'sweep floc' of amorphous hydroxide precipitate. In such systems insufficient contact opportunities exist to produce aggregates of even completely destabilised particles in a reasonable detention time (O'Melia and Stumm, 1967 and Stumm and O'Melia, 1968) so that destabilisation with lower coagulant dosage is not effective. Alternatively, the colloid concentration in such systems may be increased by addition of coagulant aid to increase the rate of interparticle contact and the destabilisation is brought about by adsorption and charge neutralisation with a lower dosage of primary coagulant.

(iv) Low Colloid Concentration and Low Alkalinity

Coagulation is most difficult in such systems. Alum or ferric salt will be ineffective if used alone, since

the pH will be decreased too low to permit rapid formation
of 'sweep floc' and the rate of interparticle contact is
presumably too slow to utilise destabilisation by charge
neutralisation. Additional alkalinity, additional colloid
particles or both must be added to provide effective
coagulation.

4.2.3. Lime as Prime Coagulant

In case of lime, coagulation is accomplished by
simple enmeshment of colloids in precipitates of $CaCO_3$ and
at higher pH of $Mg(OH)_2$. Systems having low colloid
concentration and low alkalinity may be clarified by lime
as the alkalinity increases with the addition of lime and
coagulation is readily accomplished with high dosage of lime
by enmeshment of colloids in the 'sweep floc' of $CaCO_3$.

4.2.4. Organic Polyelectrolytes

The use of natural and synthetic polyelectrolytes
to destabilise colloids in water and wastewater treatment
has become common. Important natural polyelectrolytes include
polymers of biological origin and those derived from starch
products, cellulose derivatives and alginates. Synthetic
polyelectrolytes consists of monomers that are polymerised
into high molecular weight substances. The mechanisms of
destabilisation of colloids by polyelectrolytes are by
specific adsorption and charge neutralisation, forming
particle-polymer-particle complexes or by coagulation-
bridging as has been discussed earlier. There is a direct

stoichiometric relationship between optimum polyelectrolyte dosage and colloid concentration and restabilisation due to overdosing may occur in many cases.

Depending on whether their charges, when placed in water, is positive, negative or neutral, the polyelectrolytes are classified as cationic, anionic and non-ionic or neutral respectively.

The ability of a polyelectrolyte to act as a coagulant depends upon its ability to bind itself to the surface of the colloid particle. In many cases the polymers are quite specific. Bonds may be formed between particular functional group on the polymer and specific sites of the colloid surface. Some other important parameters which affect the performance of a particular polymer are its molecular weight and degree of branching. Heavy floc is produced by both anionic and cationic polymers and the destabilisation of colloids by the polymers depends upon system characteristics like pH, concentration of divalent cations like Ca^{++}, Mg^{++}, etc. (McGarry, 1970). There is strong evidence that divalent metal ions like Ca^{++}, Mg^{++}, etc. are generally necessary for anionic polymers to flocculate negative colloids (Black et.al., 1965 & Sommerauer et.al., 1968). Posselt, Reidies and Weber (1968) have shown that divalent metal ions can also produce significant effects with respect to the coagulation of negatively charged colloids by cationic polymers. Anionic polymers are powerful coagulants for

both negatively and positively charged colloids. In addition, they are usually employed for the improvement of floc properties formed by the addition of trivalent salts. The optimum dosage of the polyelectrolyte increases with alum dosage (Committee Report, 1971). Cationic polyelectrolytes, on the other hand, can act both as a prime coagulant and coagulant aid since, in general, the colloids in water and wastewater are negatively charged. Polyelectrolytes are also believed to provide charged nuclei inducing aggregation of microflocs and improves floc strength, its resistance to attrition and dewatering properties.

5. MATERIALS AND METHODS

5.1. Materials

5.1.1. Feed Water to Washery, Feed to Thickener, Wastewater and Effluent From Washery

Samples of feed water, feed to thickener, wastewater and effluent from Patherdih, Dugda, and Bhojudih coal washeries were collected at the respective sources and brought to Central Mining Research Station (CMRS) laboratory for their characterisation. Samples of the wastewater from Patherdih washery were also used in settling column tests for the evaluation of the efficiency of the settling ponds of the washery. Thickener efficiency of the washery was evaluated by zone settling tests (with or without the addition of various coagulants) using the feed to thickener.

5.1.2. Reconstituted Samples

(i) Wastewater

As it was very difficult to transport the large quantities of wastewater sample required for the various experiments, solids from the wastewater of Patherdih coal washery were brought to the Environmental Engineering Laboratory, I.I.T., Kanpur, so that wastewater samples might be reconstituted whenever required. With the prior knowledge of the characteristics of the wastewater in respect of pH, suspended solids content, hardness, alkalinity, etc. the solids were mixed with a mixture of distilled water and laboratory tap water (alkalinity and hardness of which were

known) and the hardness and pH of the reconstituted sample were adjusted with the addition of $CaCl_2$ and $0.01N$ H_2SO_4. Reconstituted wastewater samples were employed in the extended plain sedimentation studies.

(ii) Effluent

Solids from the effluent of Patherdih coal washery were used to reconstitute the effluent sample in a similar manner and used for coagulation and extended plain sedimentation studies.

5.1.3. Coagulants and Polyelectrolytes

Alum, ferric chloride and lime were used as prime coagulants in the coagulation studies. Stock solutions of 10,000 mg/l of the coagulants were prepared and aliquots were diluted with distilled water to have desired concentration of the coagulants for the experiments.

Polyelectrolytes used in the studies were Morarfloc A, Morarfloc A-40 H, Califloc A, Nirmali seed and Coagulant X. Stock solutions of the polyelectrolytes were prepared by vigorous stirring of a known quantity of the polyelectrolyte in distilled water as instructed by the manufacturer/supplier. Nirmali seed stock solution was prepared from the powdered seed according to the procedure recommended by Tripathy, Choudhuri, and Bokil (1976). Diluted polyelectrolyte solutions of desired low concentrations were used in the experiments. Details of the coagulants and polyelectrolytes used are shown in Table 7.

Table 7. Coagulants and Polyelectrolytes

Name	Formule	Properties/ Grade	Name of the manufacturer/ Supplier
Alum	$Al_2(SO_4)_3, 15H_2O$	Annalar	BDH, India.
Ferric Chloride	$FeCl_3, 6H_2O$	Laboratory Reagent	Thomas Baker and Co., London.
Lime	CaO	Technical	BDH, India.
Morarfloc A	–	Non-ionic	Dharamsi Morarji Chemical Co.Ltd.,Bombay.
Morarfloc A-40 H	–	Anionic	Dharamsi Morarji Chemical Co.Ltd.,Bombay.
Califloc A	–	Anionic	Plastics and Fibres Division, Calico Chemicals Bombay.
Nirmali seed	–	Anionic	Maharastra Engineering Research Institute, Nasik.
Coagulant X	–	–	Prof.A.K.Ghose, Indian School of Mines, Dhanbad.

5.2. Methods

5.2.1. Characterisation of Washery Feedwater, Wastewater and Effluent

Suspended and disolved solids concentrations, pH, hardness, and alkalinity of the feedwater, wastewater and effluent were evaluated following the standard analytical procedures given in the Standard Methods (1976). Screen analysis of the suspended solids in normal sieve range was performed by wet screening method because of the surface adherence of the fine solids and also the blinding of the screen cloth (Banerjee et.al., 1964). The slurry was poured on the 30 mesh BSS sieve held over an enamelled bucket, water was sprayed over the slurry on the screen and the slurry agitated until the underflow became free from solid particles. Under sized solids collected in the diluted slurry in the bucket was similarly treated over the next screen (60 mesh BSS) and the operation repeated with successive screens upto 300 BSS. All the solid fractions were dried in an air oven and the weight percentage of each were determined. Sub-sieve range analysis of the -300 mesh BSS fraction of the solids were performed with a sedimentation method. A portion of thoroughly mixed slurry containing -300 mesh solids was taken in a 500 ml graduated cylinder and slurry containing solids, settled through a fixed height, were pipeted out at definite intervals of time. The pipeted out samples were dried in an air oven and their weight recorded. The weight percentage of solids

of a particular diameter range was calculated from the formula:

$$d = 234 \sqrt{\frac{h}{t}}$$

where, d = minimum diameter of the particles falling to the

fixed point of sampling;

h = mean height of fall of the particles, cm; and

t = time of fall, sec.

The formula has been derived from Stock's law, assuming the specific gravity of coal to be 1.25 and conducting the experiments near about $20^{\circ}C$.

The data relating to the characteristics of the washery feedwater, wastewater and effluent have been presented in chapter 2.

5.2.2. Wastewater Flow Measurement

The flow of the Patherdih coal washery wastewater to the settling ponds was measured by means of a 90° triangular notch made of a thin and strong steel plate. The notch was placed rigidly in the open channel carrying the wastewater to the settling ponds. The water level in the notch was noted and the discharge calculated according to the formula (Addison, 1959):

$$Q = 0.0146 \ H^{2.48}$$

where, Q = discharge, litre/sec; and

H = height of the water level from the inverted

apex of the notch, cm.
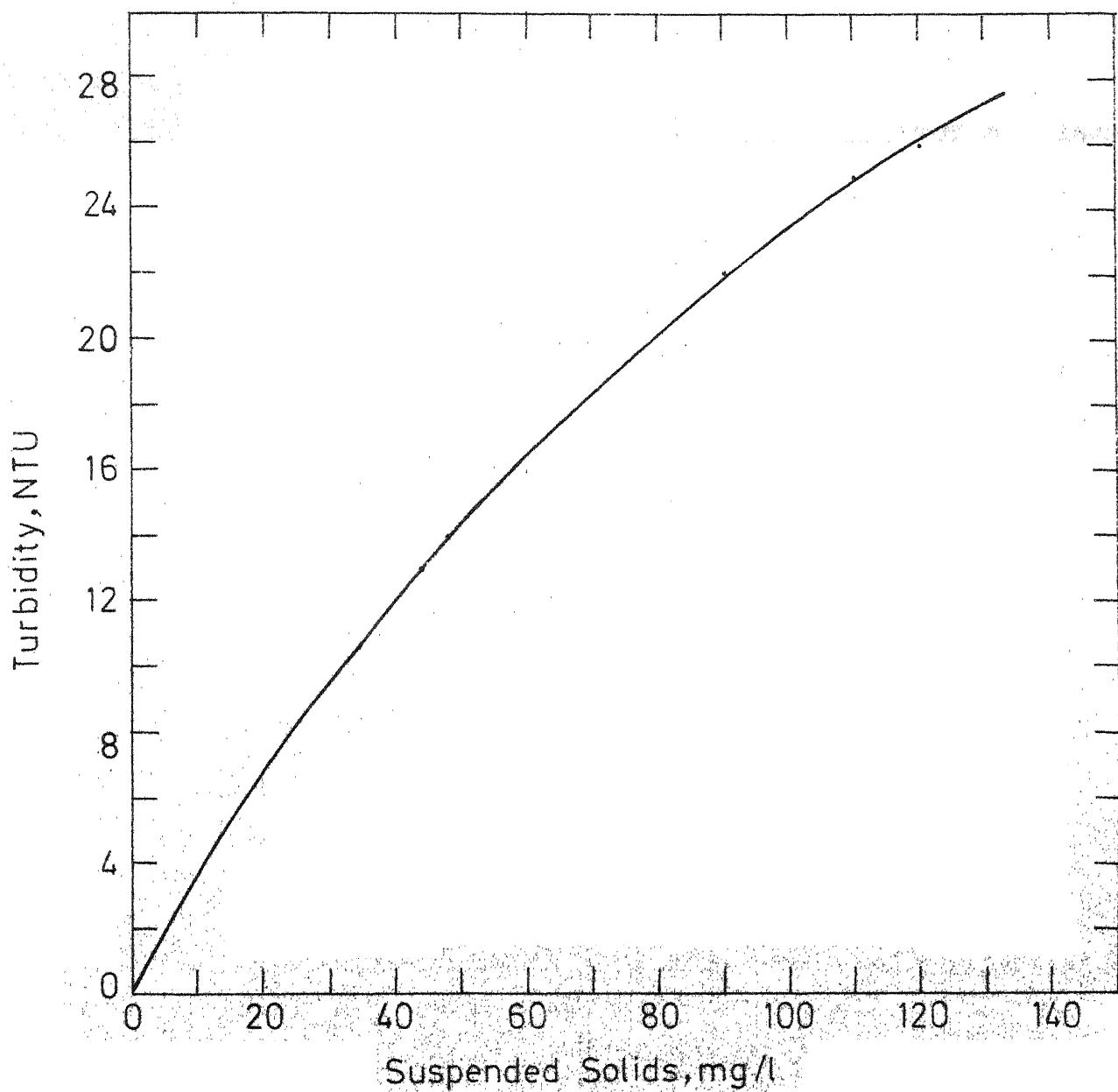
Fig. 11. Relationship Between Turbidity and Suspended
Solids for Patherdih Coal Washery Effluent

procedure suggested by Zanoni and Blomquist (1975). These experiments were conducted in the CMRS laboratory using actual wastewater samples. A thoroughly mixed wastewater sample was placed in a 7.6 cm (ID) tall plastic column of 170 cm length with seven sampling ports 23 cm apart from each other. The sampling ports were provided with small rubber stoppers through which were inserted short sections of glass tubings and kept sealed using short sections of rubber tubings and pinch clamps. At the start of the experiment, the suspended solids concentration was same throughout the column. The suspension was allowed to settle under quiescent condition and samples were withdrawn through the sampling ports at 10 min intervals. After trying several sampling procedures, it was found that a modified 10 ml syringe with a narrow metal tube suitable for insertion through the rubber tubings of the sampling ports to reach the centre of the column provided an excellent means of obtaining a known volume of the sample with minimal disturbance. Special precautions were taken while withdrawing samples from the lower sampling ports where the liquid pressure tended to push out the piston of the syringe. The suspended solids concentrations of the samples were determined by filtering through 0.45 μm membrane filter. Percent suspended solids settled out were plotted against their respective time and depth and isopercentage lines were drawn.

5.2.5. Coagulation Studies

Coagulation studies using reconstituted Patherdih washery effluent samples were conducted to find out the optimum dosages of coagulants like alum, ferric chloride and lime separately and in combination with low concentrations (0.01 - 1.0 mg/l) of polyelectrolytes such as Morarfloc A, Morarfloc A-40 H, Califloc A, Nirmali seed and Coagulant X as well as the optimum dosages of these polyelectrolytes as prime coagulants. The coagulation experiments were conducted using a six-place multiple stirrer (Phipps and Bird Inc., Richmond, Va.) using rapid mixing @ 100 rpm for 1 min followed by 20 min of slow mixing @ 20 rpm and a quiescent settling for 30 min. Samples (50 ml) for turbidity and pH measurements were withdrawn from each jar at the end of the quiescent settling period. The first jar always served as a control. A turbidimeter (Model ?100A, Hach Chemical Co., Ames, Iowa) was employed for turbidity measurements. The pH of the samples were measured with a Philips single electrode pH meter which was standardised with standard buffer solutions before use.

5.2.6. Extended Plain Sedimentation

The experimental studies were performed according to the procedure described by Yao (1975). A portion of the wastewater or effluent sample was placed in a 7.6 cm (ID) plastic column of 90 cm height with a sampling port at a distance of 6 cm from the closed bottom. A small portion of the slurry was discarded before each sampling to drain

out the slurry already present in the sampling tube. The open mouth of the column was closed after filling with the reconstituted sample (effluent or wastewater) and it was turned end over end so as to make the concentration of the suspended solids same throughout the column. A sample was pipeted out quickly and was analysed for the initial suspended solids concentration. Sampling schedule was 1 hr, 2 hr, 4 hr, 6 hr, 12 hr, 24 hr, 48 hr, and 72 hr. Each time two 30 ml samples, one from the surface and the other from the sampling port, were taken and the temperature of the liquid column was also noted. Suspended solids concentrations of the initial samples were measured by filtering a 25 ml sample through a 0.45 μm membrane filter. Turbidity measurements were used for the samples of low suspended solids concentration and the turbidity values were converted to suspended solids concentration using the calibration curve (Fig. 11).

5.2.7. Zone Settling Experiments

Zone settling tests were conducted in the CMRS laboratory using actual samples of feed to the thickener of the Patherdih coal washery. The tests were performed in 500 ml measuring cylinders graduated in mm. In the procedure, a cylinder was filled with a thoroughly mixed sample followed by coagulant addition (when used) and immediate mixing of the content by turning the cylinder end over end. The sample was then allowed to settle in the cylinder under quiescent condition. The time required for the settling of the solid interface was noted till no appreciable fall was observed.

6. RESULTS AND DISCUSSION

Results of all the experiments are presented in graphical or tabular form. In order to make it clearly understandable, a discussion of the results follows each phase of the experimental work.

6.1. Settling Pond Efficiency

The largest settling pond of the Patherdih coal washery, 7.6 m (length) x 6.1 m (width) x 0.91 m (depth), was selected for pond efficiency evaluation using the column settling test results (Fig. 12 and 13). The rate of discharge of wastewater to the pond was measured by a triangular notch and was found to be 14.15 litres/sec. Theoretical detention time was 50 min. Under these conditions, the theoretical overall suspended solids removals computed from Fig. 12 and 13 are 97.58 and 95.41 percent for initial suspended solids concentrations of 8710 and 7580 mg/l, respectively. This would mean a pond effluent of suspended solids concentration in the range 200 - 400 mg/l if the pond is functioning with theoretical efficiency and influent suspended solids concentration in the range 7580 - 8710 mg/l. However, the effluent sample analysis shows that the suspended solids concentration is more than 1000 mg/l (Table 6). Decreased removal of suspended solids is presumably due to a much lower actual detention time than the one calculated using pond geometry and the rate of wastewater inflow. This is primarily due to the method of operating the settling ponds which allows a pond to nearly
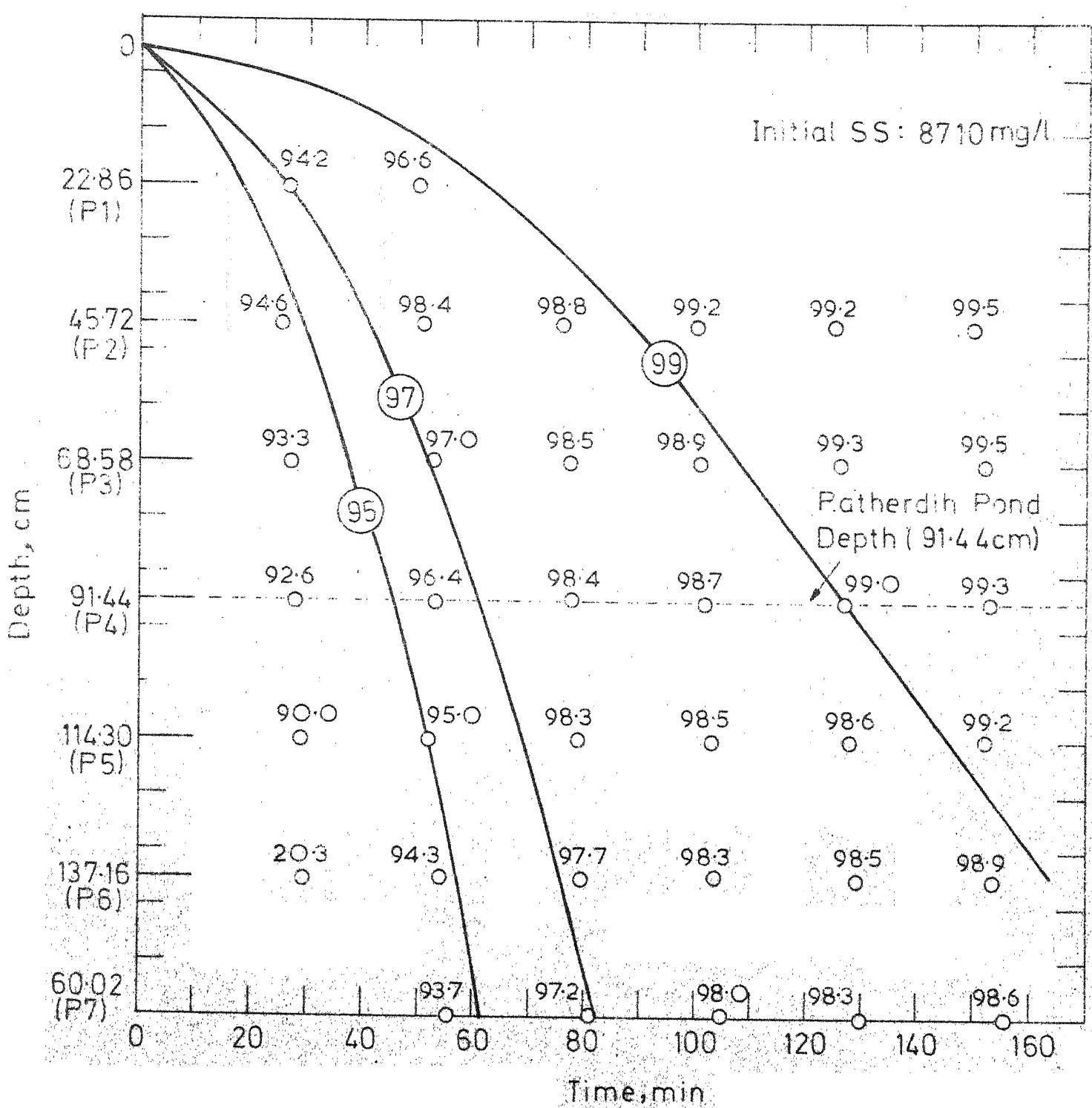
Fig.12. Settling Curves for Patherdih Washery Waste Water
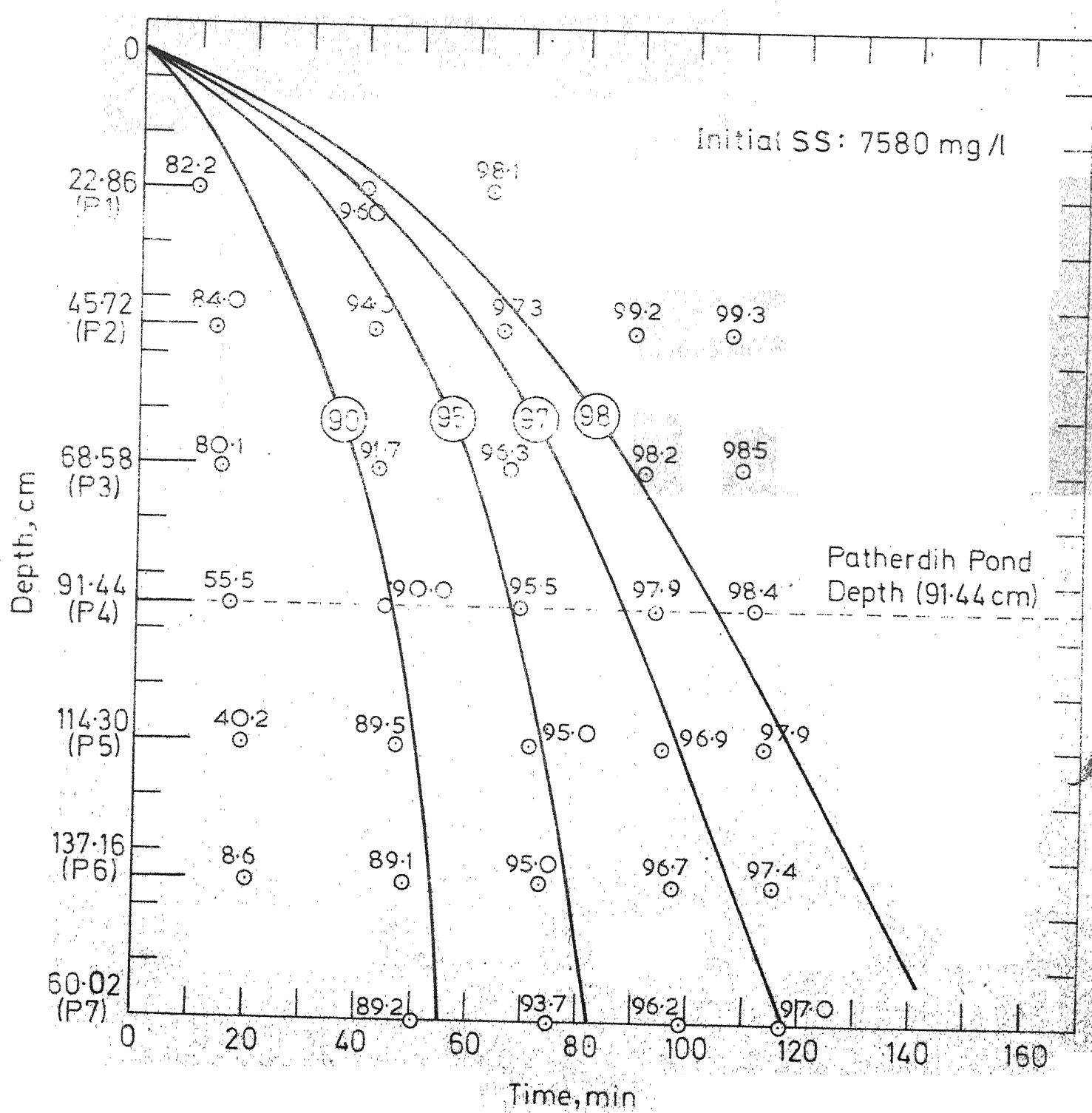
Fig.13. Settling Curves for Patherdih Washery Waste Water

fill up before the wastewater is diverted to another pond.
This reduces the detention time consideraly. Scouring may
also occur due to the reduction of the depth of the pond
thereby increasing the effluent suspended solids concentration.

It is also apparent from this phase of the study
that the settling pond effluent may not satisfy the discharge
requirement of 100 mg/l suspended solids concentration
(IS:2490-1974) even when the settling ponds function with
theoretical efficiency. This would mean further treatment of
the effluent with an added objective of inplant reuse of the
effluent, if possible. Two candidate methods, viz., chemical
coagulation and extended plain sedimentation were evaluated
in this regard. Also, the wastewater was subjected to plain
sedimentation studies to investigate whether the present
settling ponds may be operated as extended plain sedimentation
basins directly to meet the discharge requirements.

6.2. Effluent Treatment by Coagulation

The results of the coagulation studies on
reconstituted Patherdih washery effluent using various
coagulants and polyelectrolytes are shown in Fig. 14 - 22.
The initial suspended solids concentration for each experimental
run is indicated in parenthesis against each coagulant.

It is seen from Fig. 14 that among the chemical
coagulants used, alum with a dosage of 50 mg/l was most
effective and produced a supernatant having a turbidity of
0.4 NTU. Ferric chloride with a dosage of 40 mg/l resulted
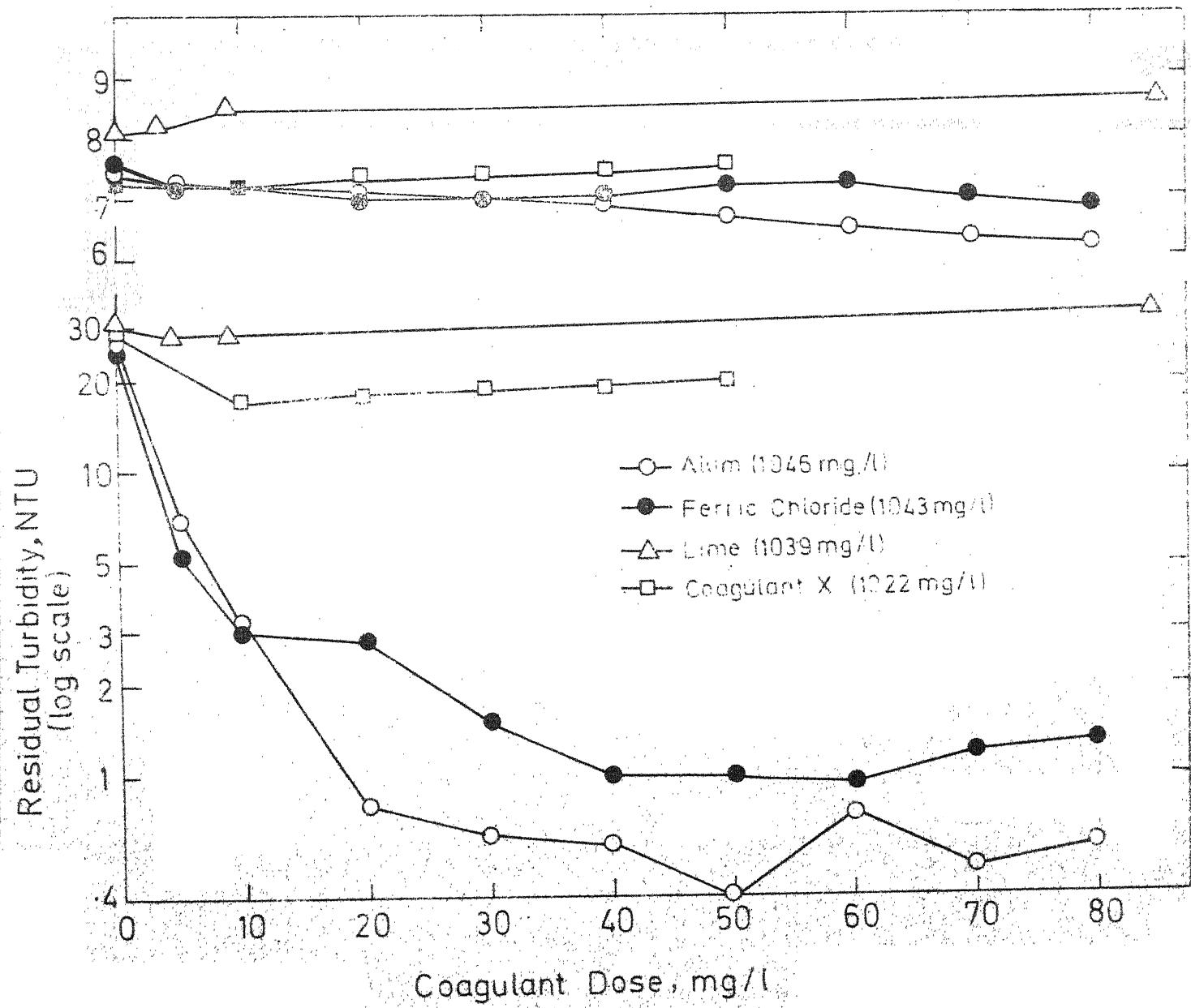
Fig.14. Clarification of Coal Washery Effluent Using Chemical Coagulants

in a supernatant turbidity of 1.0 NTU whereas the turbidity
of the supernatant was almost unaffected for any dosage of
lime. Referring to Fig. 11, it is seen that the suspended
solids concentration corresponding to 1.0 NTU turbidity is
less than 5 mg/l and hence either alum (50 mg/l) or ferric
chloride (40 mg/l) may be used for coagulation of the effluent.
However, the choice will depend on the economic and other
practical considerations. Among the polyelectrolytes used as
prime coagulants (Fig. 15), Califloc A and Nirmali seed were
most effective with dosage of 0.2 and 0.5 mg/l, respectively
and produced residual turbidity of 14.0 NTU which corresponds
to a suspended solids concentration of 48.0 mg/l (Fig. 11).

Regarding the use of polyelectrolytes as coagulant
aids in combination with alum, ferric chloride or lime (Fig.
16 - 20), the following observations may be made:

(i) Anionic polyelectrolytes (Califloc A, Morarfloc
A-40 H and Nirmali seed) were effective in the
dosage range 0.01 - 0.1 mg/l in reducing the
alum dosage. Califloc A and Morarfloc A-40 H
were also effective in the same dosage range
in reducing the supernatant turbidity further,
when used with the optimum alum dosage.
Higher dosages were not effective. The nonionic
polyelectrolyte, Morarfloc A at a dosage of
0.1 mg/l was effective in reducing the optimum
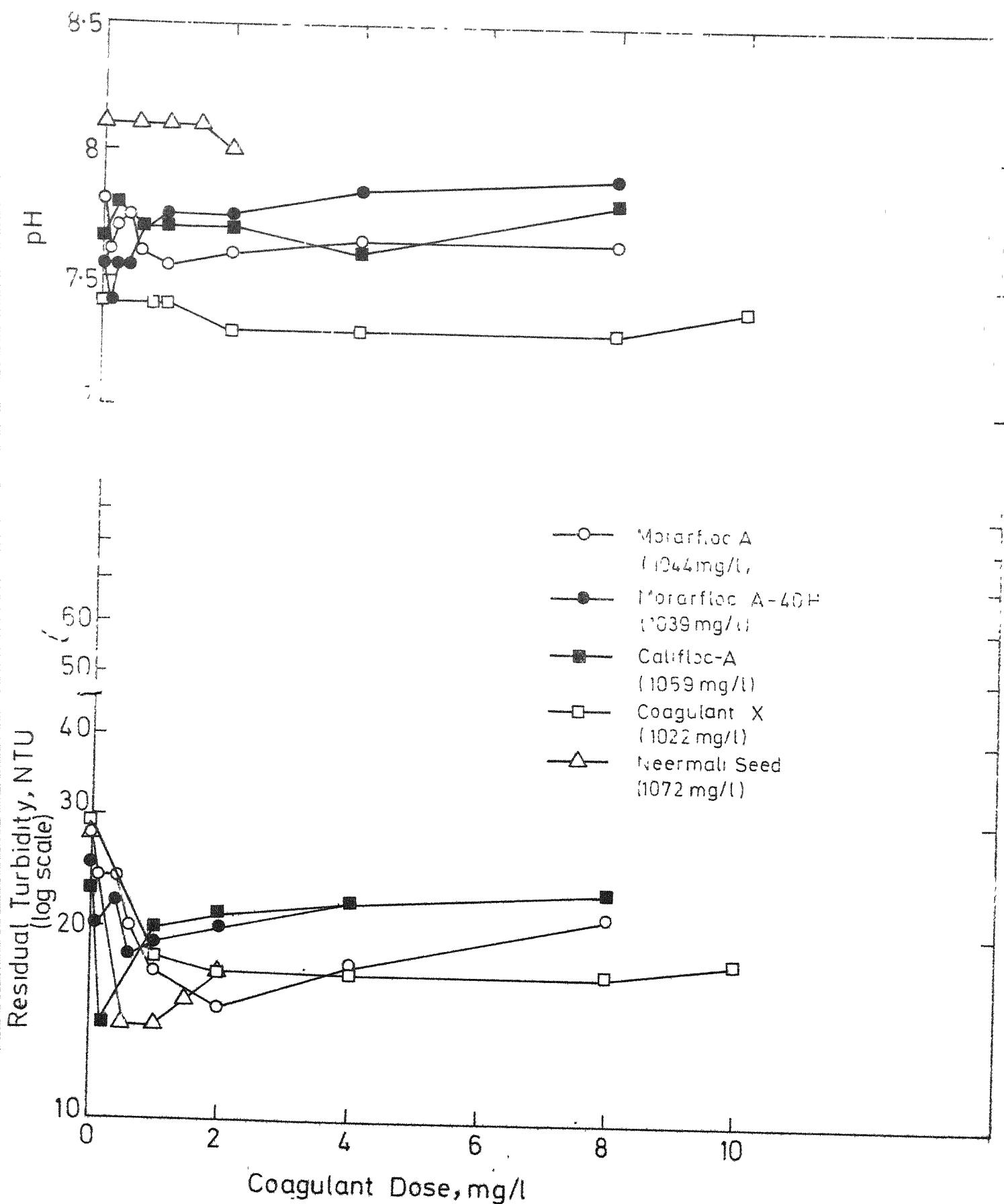
Fig.15. Clarification of Coal Washery Effluent Using Natural and Synthetic Polyelectrolytes
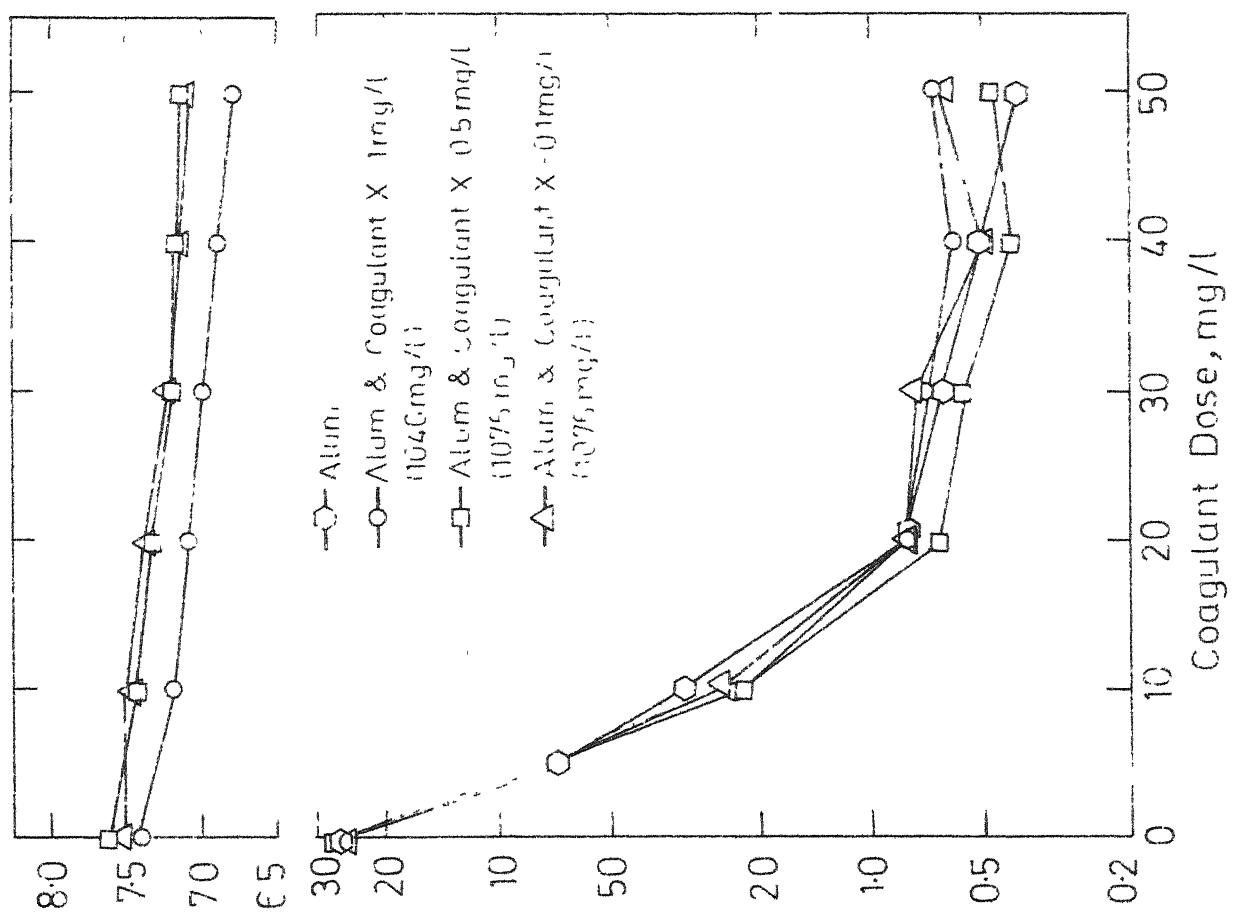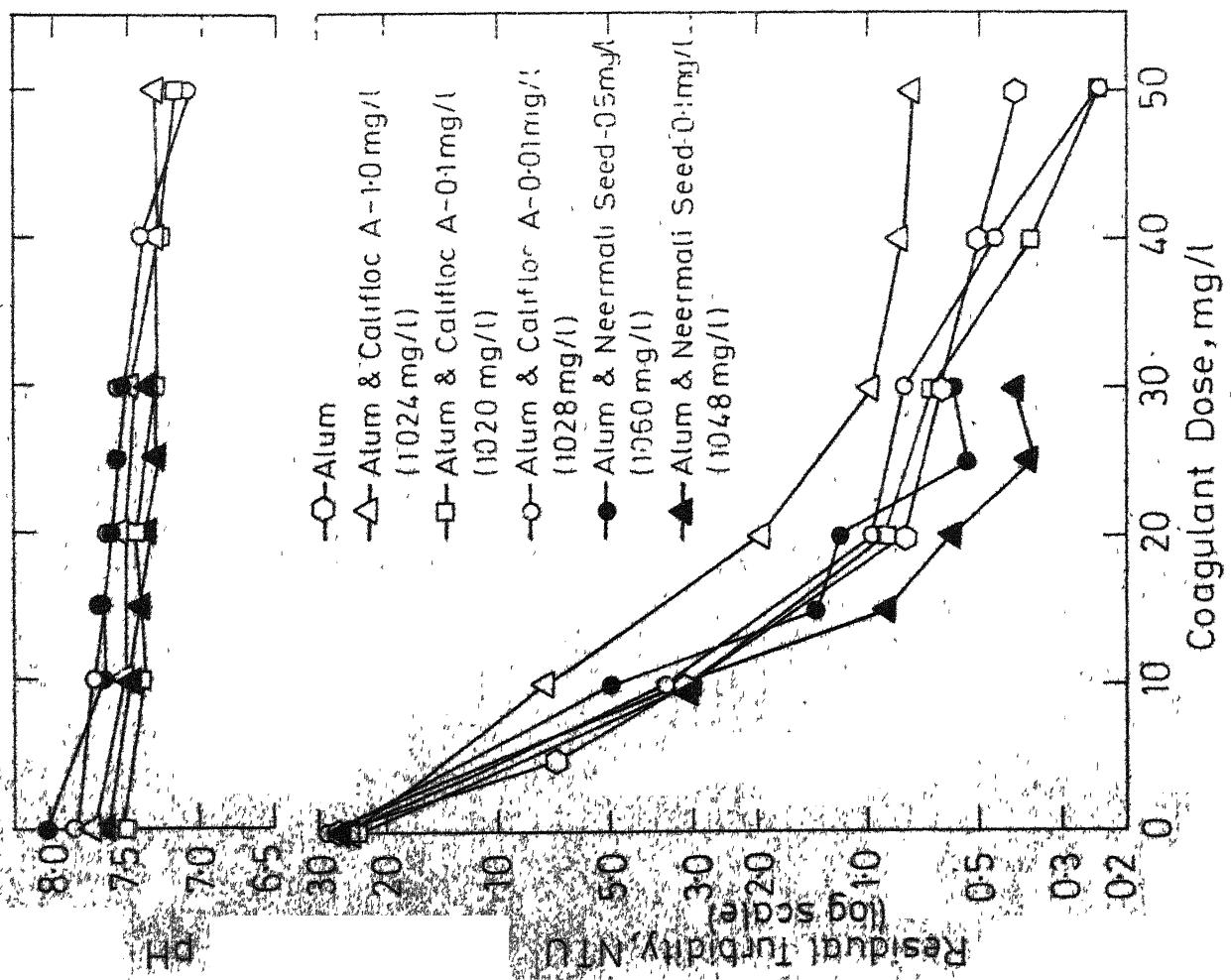
Fig.16: Clarification of Coal Washery Effluent Using Alum in Combination
With Califloc A, Neermali Seed and Coagulant X
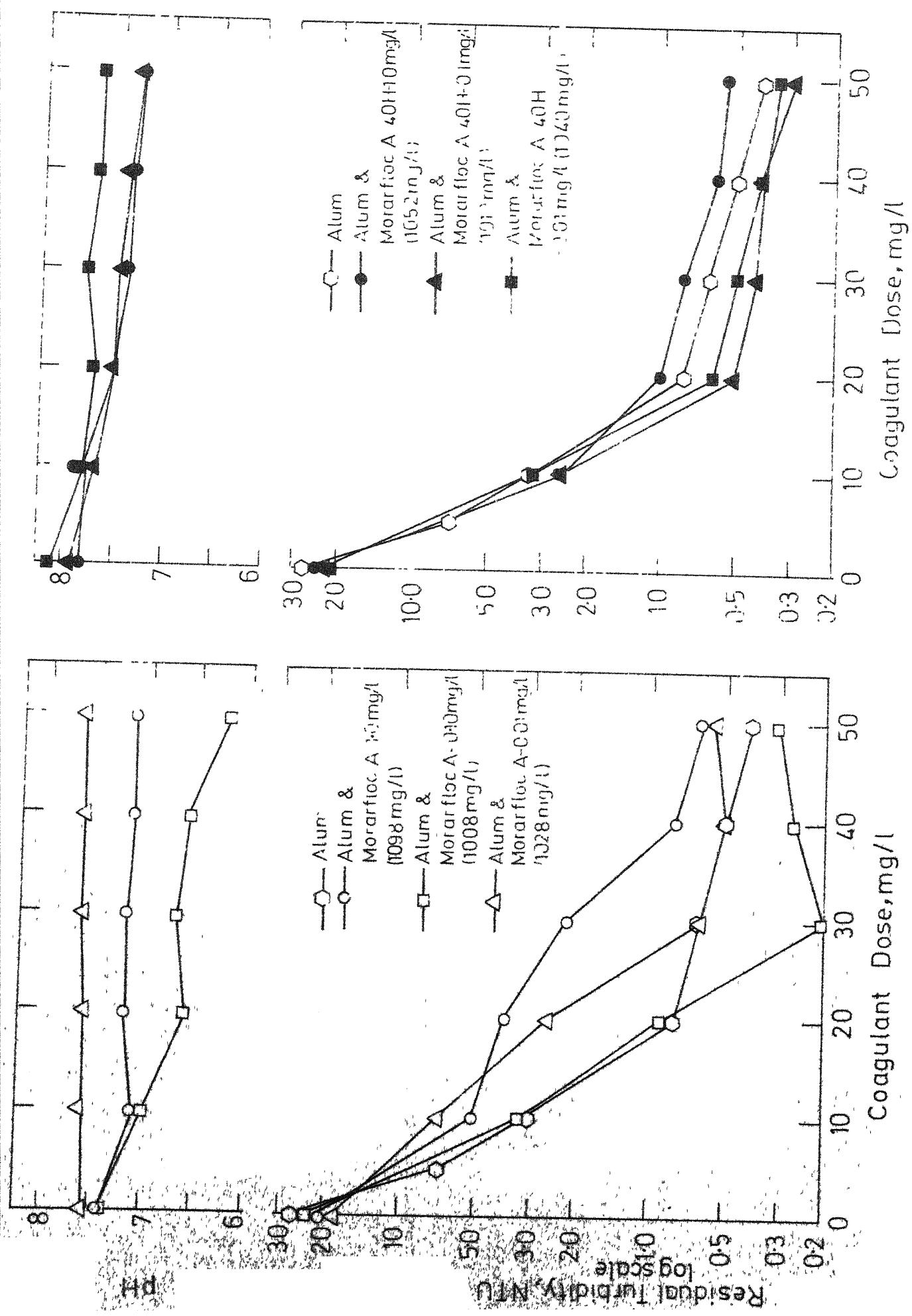
Fig. 17. Clarification of Coal Washery Effluent Using Alum in Combination With Morarfloc
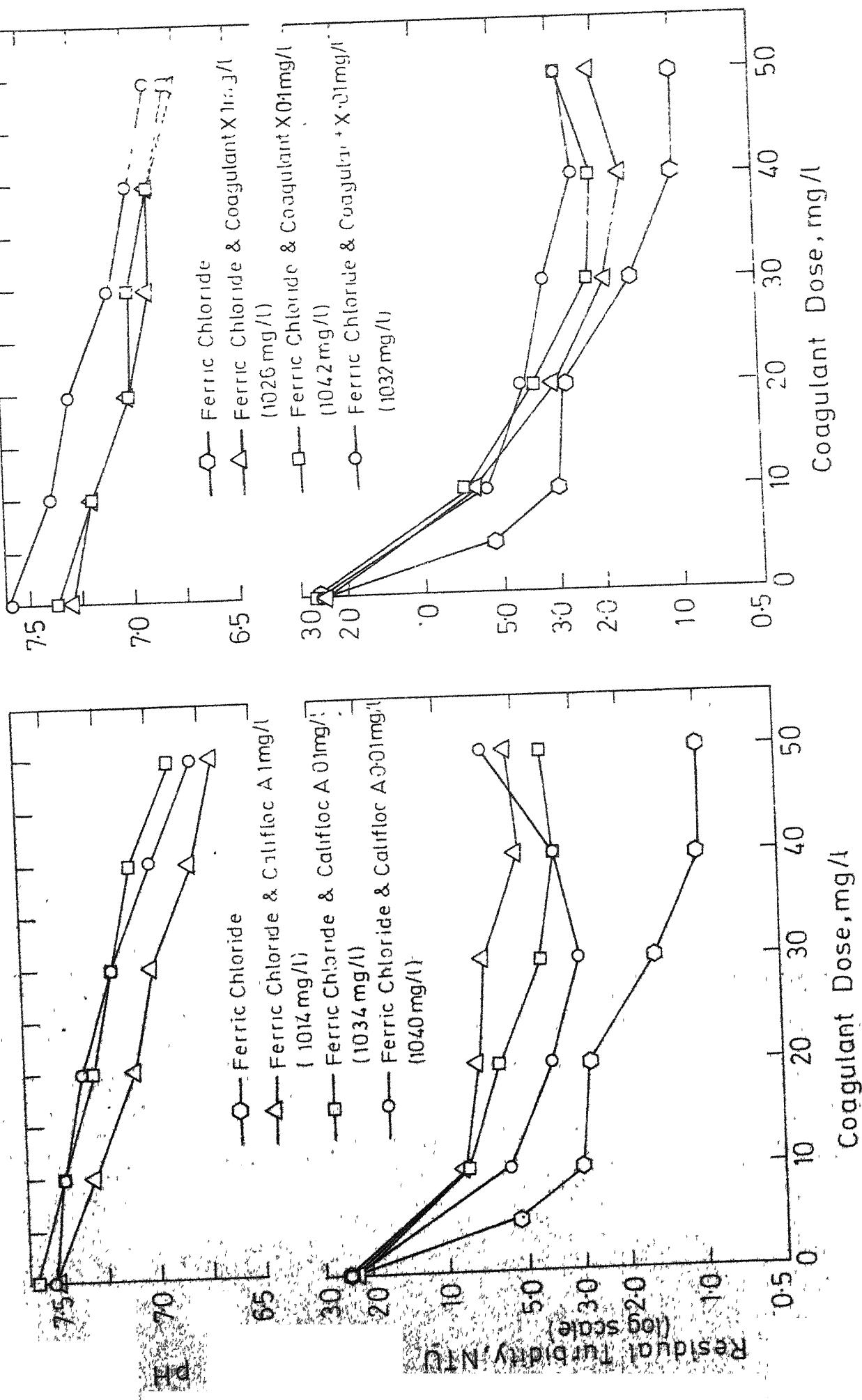
Fig.18. Clarification of Coal Washery Effluent Using Ferric Chloride in Combination with Califloc A and Coagulant X
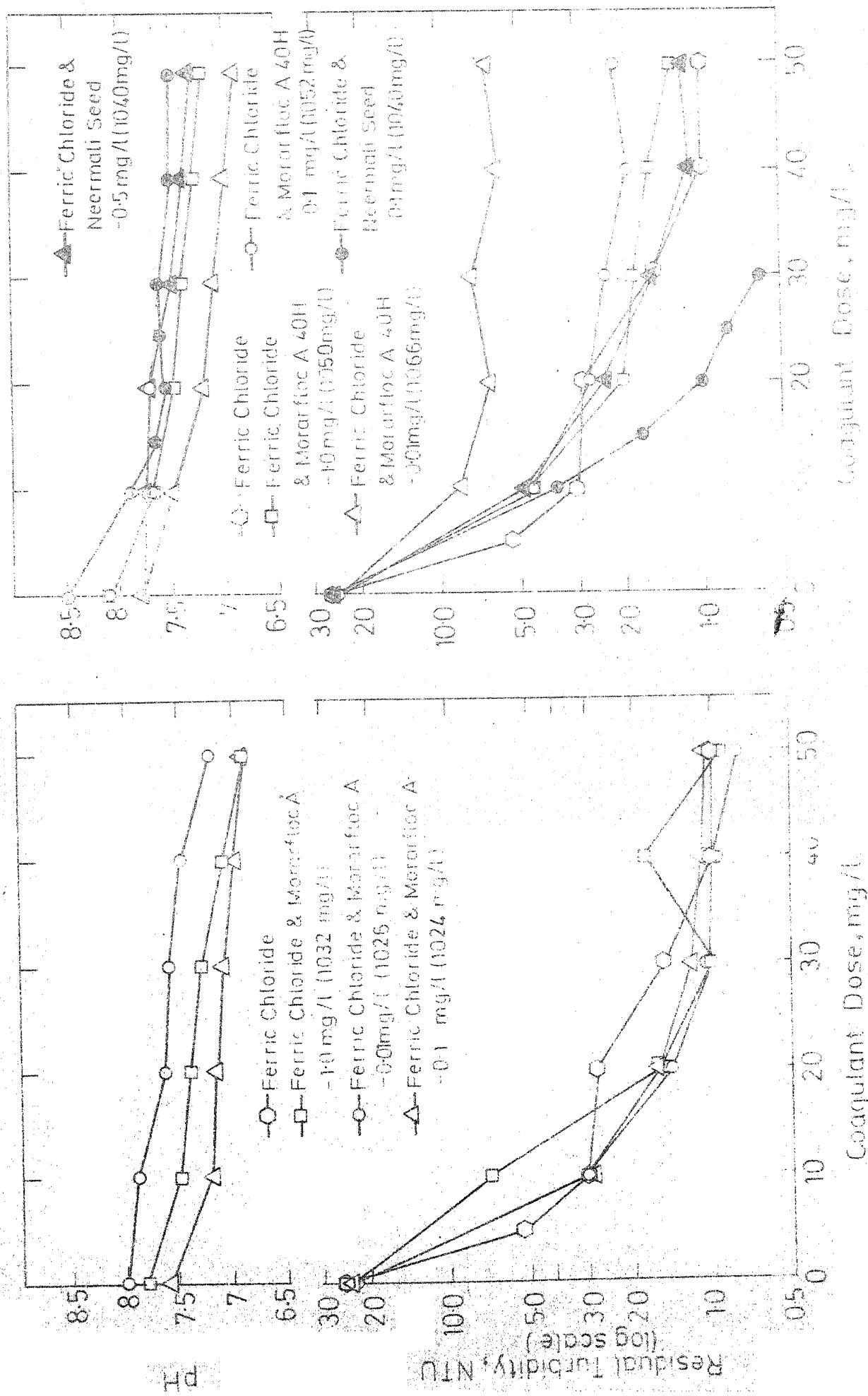
Fig.19. Clarification of Coal Washery Effluent Using Ferric Chloride in Combination With Morarfloc and Neermali Seed
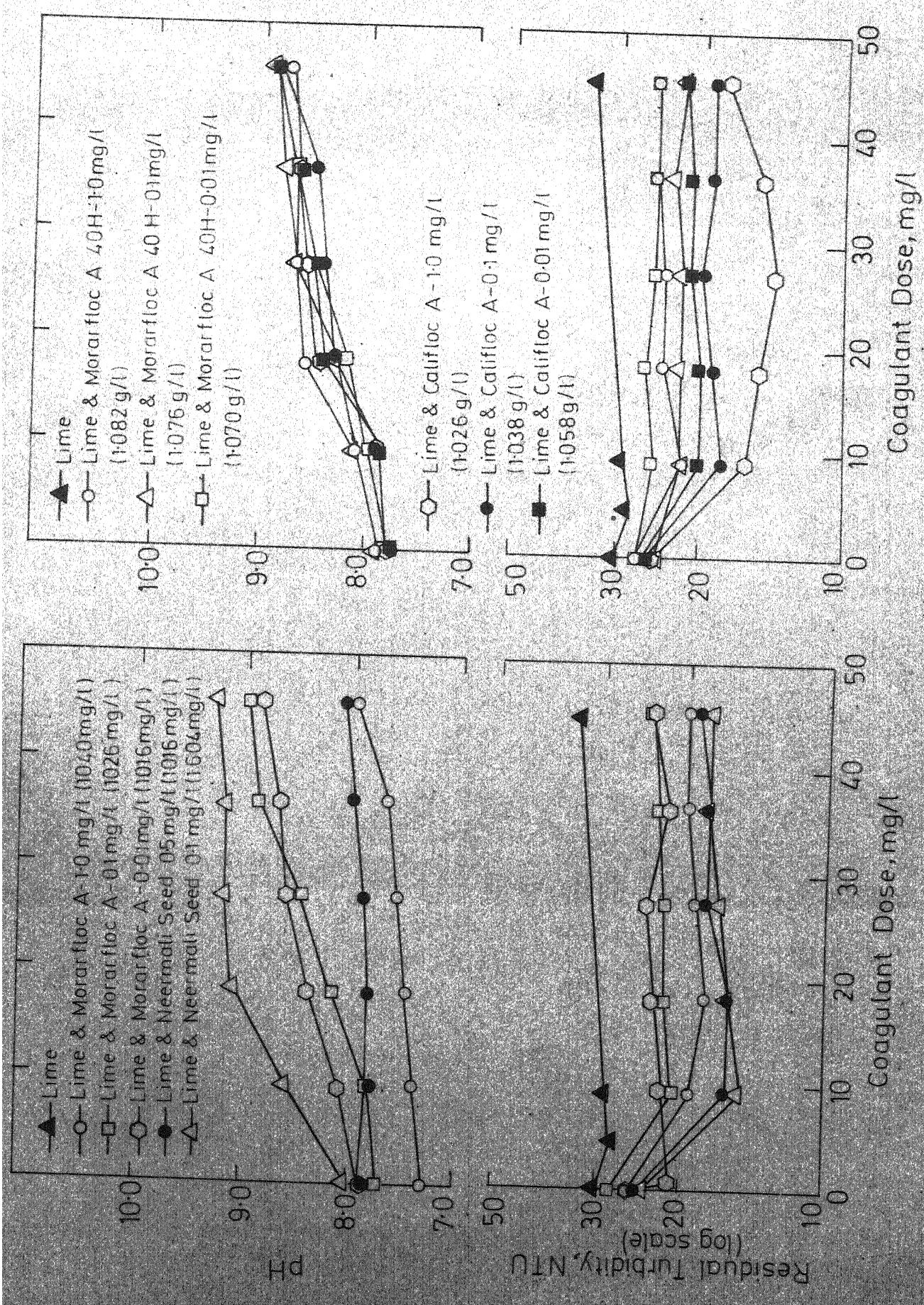
Fig 20. Clarification of Coal Washery Effluent Using Lime in Combination With Morarfloc, Califloc A and Neermali Seed

alum dosage as well as supernatant turbidity
when used with the optimum alum dosage. Dosages
above or below 0.1 mg/l were not effective. Also
coagulant X was not effective at all in the dosage
range (0.1 - 1.0 mg/l) used.

(ii) Nirmali seed was effective in reducing the optimum
ferric chloride dosage. Morarfloc A (0.01 - 1.0 mg/l)
reduced the optimum ferric chloride dosage;
however, improvement in the supernatant turbidity
removal was marginal when used with the optimum
ferric chloride dosage. The other polyelectrolytes
used, Califloc A, Coagulant X and Morarfloc A - 40 H,
were not effective at all.

(iii) All the polyelectrolytes used in combination with
lime, e.g., Morarfloc A, Nirmali seed, Morarfloc
A - 40 H and Califloc A, were effective in reducing
the supernatant turbidity when used in combination
with lime even though lime alone was not at all
effective. However, the supernatant turbidity
never went below 14.0 NTU even in the case of the
most effective polyelectrolyte (Califloc A).

It is also evident (Fig. 16 - 20) that the optimum
dosages of alum and ferric chloride are not lowered considerably
when used in combination with the polyelectrolytes. The ash
content of the settled coal fines increases when the effluent
is coagulated with alum or ferric chloride as well as those

in combination with the polyelectrolytes. If the clarity of
the supernatant is the main criterion, alum or ferric chloride
in combination with the polyelectrolytes will be the most
suitable; however, when the recovery of the settled coal fines
is the objective for its use as coking coal, coagulation with
the polyelectrolytes as prime coagulants will be the most
suitable though in such cases the clarity of the supernatant
will be somewhat less.

In order to investigate the effects of initial
pH and suspended solids concentration on the coagulation of
washery effluent, experiments were conducted with 40 mg/l
of alum using the reconstituted effluent at various initial
pH (adjusted with H_2SO_4 or NaOH) and suspended solids
concentrations (Fig. 21 and 22). In general coagulation was
more effective at lower pH values and lower suspended solids
concentrations. Conceivably, coagulation was affected by
distabilisation as a result of adsorption of hydroxometal
polymers and charge neutralisation (Weber, 1972).

6.3. Extended Plain Sedimentation Studies

Extended plain sedimentation studies were conducted
on the reconstituted washery effluent as an alternative to
the coagulation studies. The objective was to evaluate its
potential in comparison with the coagulation process. It
was thought that the additional cost of land required for
extended plain sedimentation would be offset by the savings
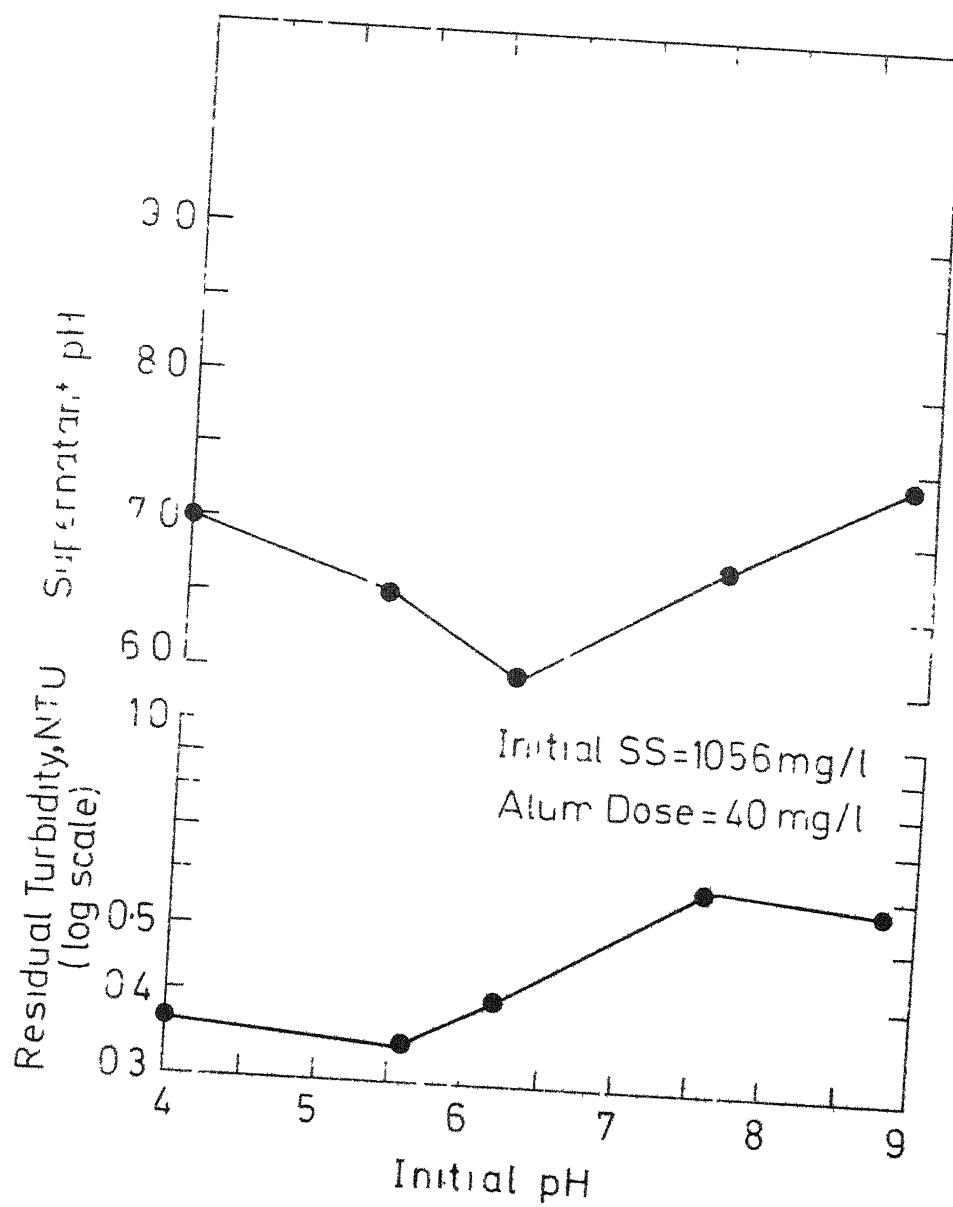
Fig 21 Effect of Initial pH on Alum
Coagulation of Patherdih
Washery Effluent
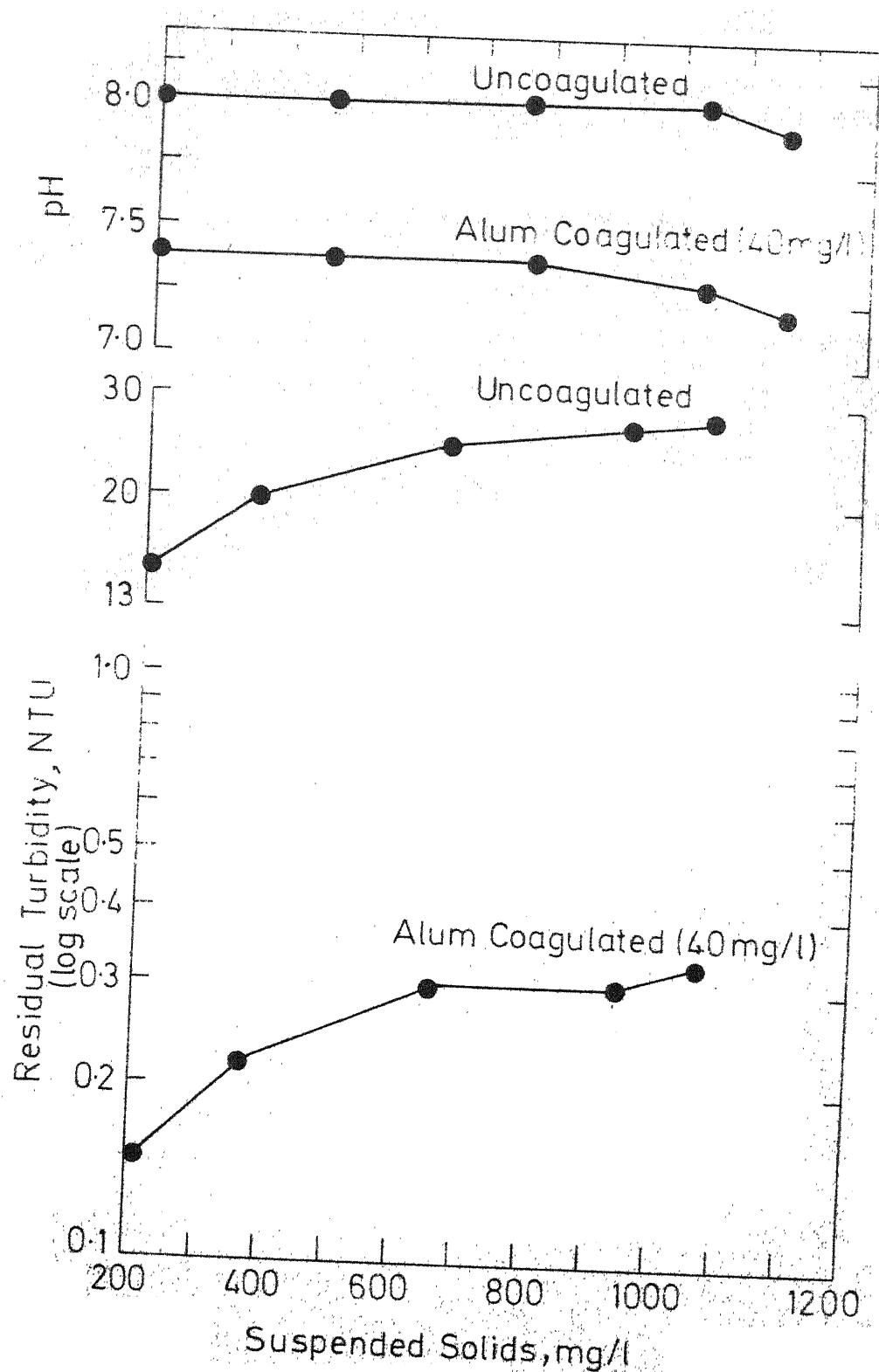
Fig.22. Effect of Initial Suspended Solids
Concentration on Alum Coagulation
of Patherdih Washery Effluent

in terms of coagulant, another advantage being no addition
to the ash content of the recovered coal fines which may
pose a problem when inorganic coagulants are used. The
reconstituted wastewater sample was also subjected to
extended plain sedimentation studies to explore the possibility
of modifying the presently used settling ponds to extended
plain sedimentation basins so as to satisfy the specified
limit (100 mg/l) of suspended solids in the effluent for
discharge.

Figures 23 and 24 show the residual suspended
solids as a percent of the initial for different overflow
rates during plain sedimentation of Patherdih washery effluent
and wastewater, respectively. These studies were conducted
using two different initial solids concentrations, viz.,
1196 and 1208 mg/l for the effluent and, 6500 and 5200 mg/l
for the wastewater. However, data for 1196 and 6500 mg/l
were plotted since the data for 1196 and 1208 mg/l for the
effluent and 6500 and 5200 mg/l for the wastewater were very
close. Since the effluent from a real settling pond will be
a mixture of the settled water from different levels throughout
its depth, the range of effluent suspended solids concentration
with respect to a particular overflow rate may be obtained from
Fig. 23 and 24 and vice-versa. It is evident that the
presently specified limit of 100 mg/l of effluent suspended
solids may be achieved through extended plain sedimentation
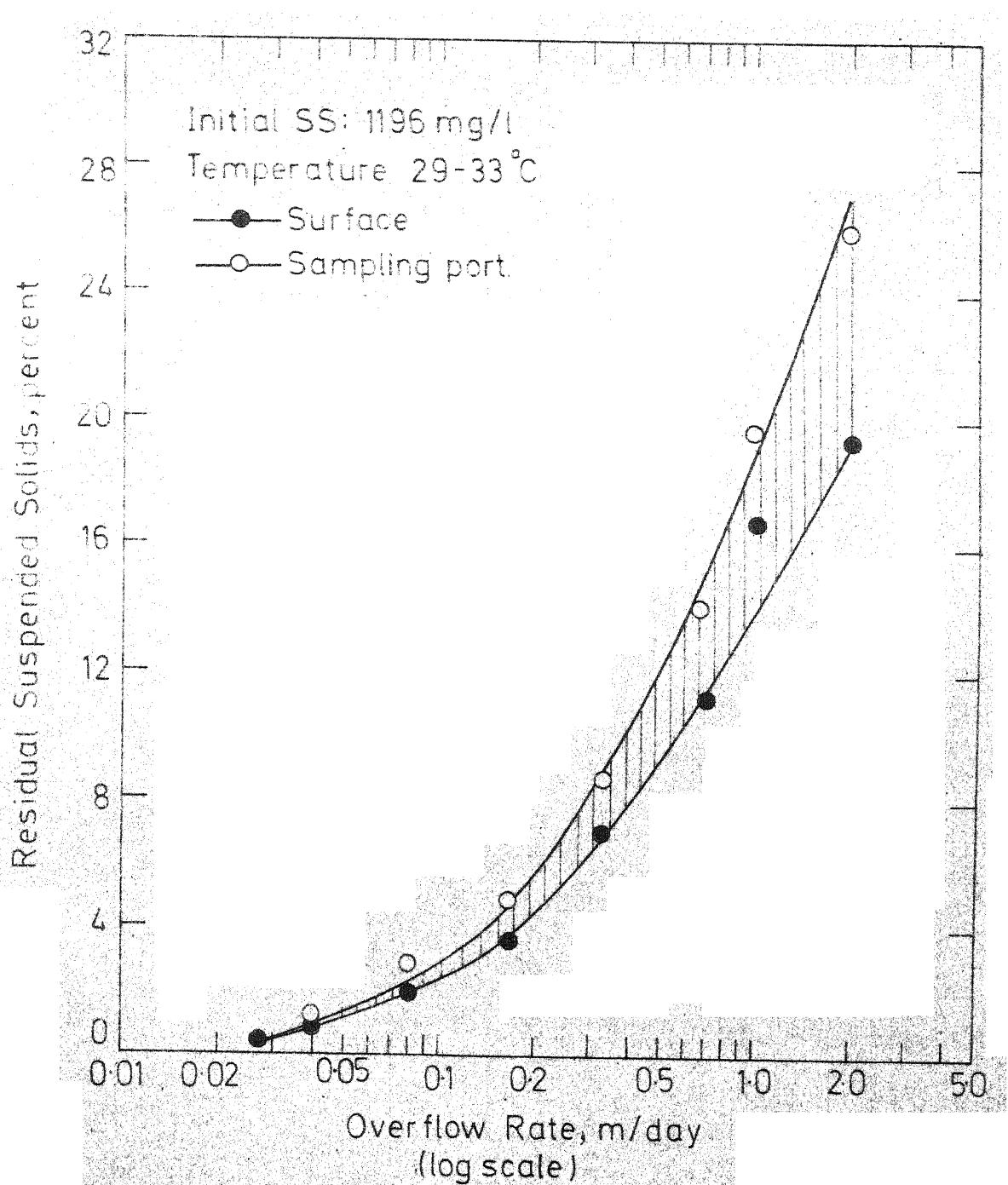
Fig. 23. Residual Suspended Solids for Different Overflow Rates During Plain Sedimentation of Coal Washery Effluent
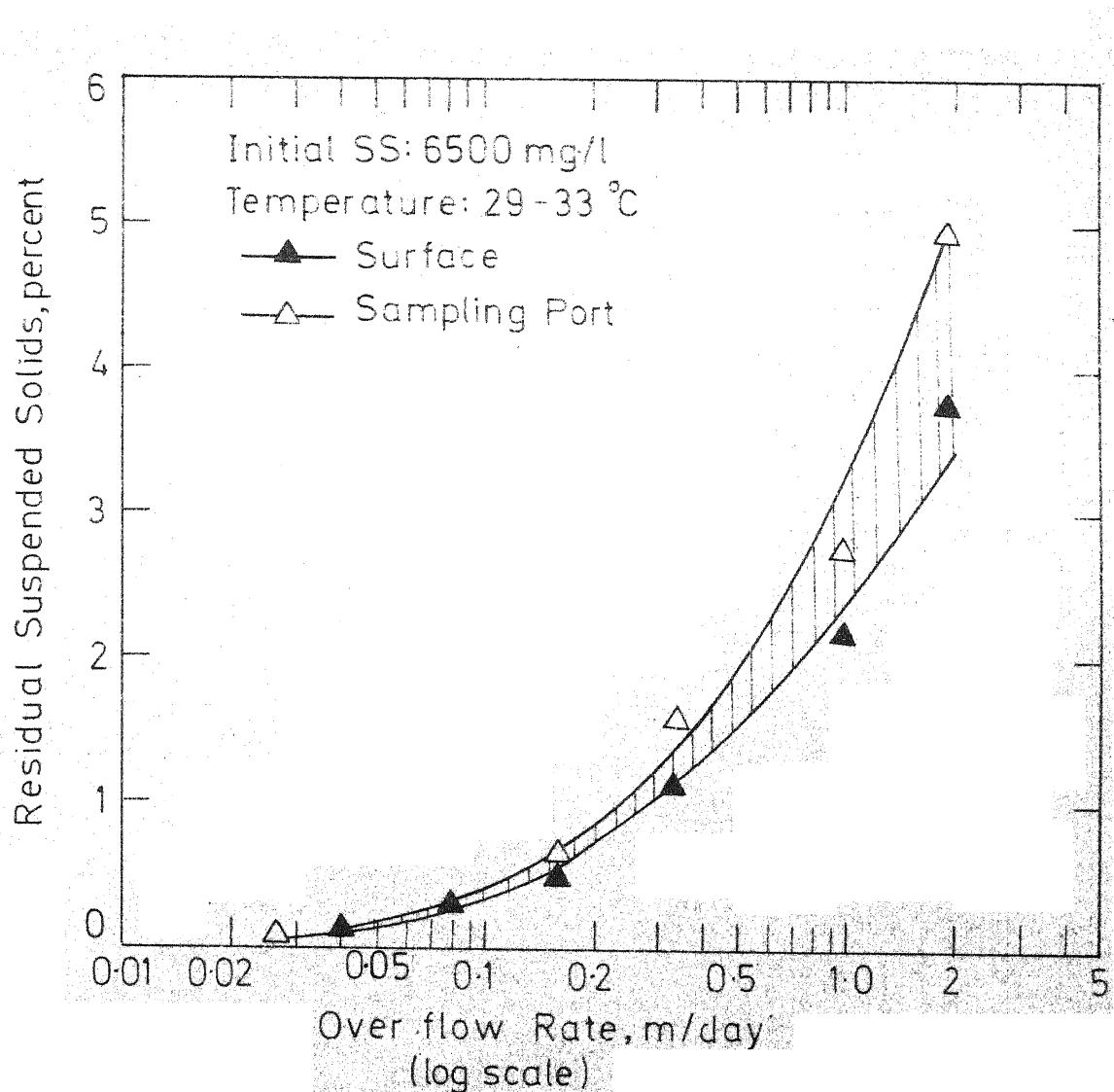
Fig. 24. Residual Suspended Solids for Different Overflow Rates During Plain Sedimentation of Coal Washery Wastewater

of the effluent from the present settling ponds or the wastewater
itself which is presently being fed to the settling ponds. The
required overflow rates will be 0.3 - 0.4 and 0.4 - 0.5 m/day
for the effluent and wastewater respectively.

6.4. Zone Settling Studies

Interface settling curves of the Patherdih coal
washery thickener feed with and without various coagulants are
shown in Fig. 25 and 26. An analysis was carried out using the
interface settling curve of the feed with lime (2.0 mg/l) in
combination with Morarfloc A (0.02 mg/l) as used presently.
It was found that the present thickener area (885 sq.m) is
more than adequate to produce the desired underflow concentration
of 500,000 mg/l. It would appear that by reducing the rate of
underflow pumping it may be possible to obtain a higher underflow
concentration thereby reducing the suspended solids concentration
of the wastewater which along with spill water is presently being
treated in the settling ponds. Also, it may be said from the
other curves using Nirmali seed and Morarfloc A as coagulants
that it is possible to achieve a higher underflow concentration
even with the present rate of sludge pumping by judicious
manipulation of coagulant addition. However, a detailed
inplant study is in order for more specific recommendation
regarding the operation of the thickener.
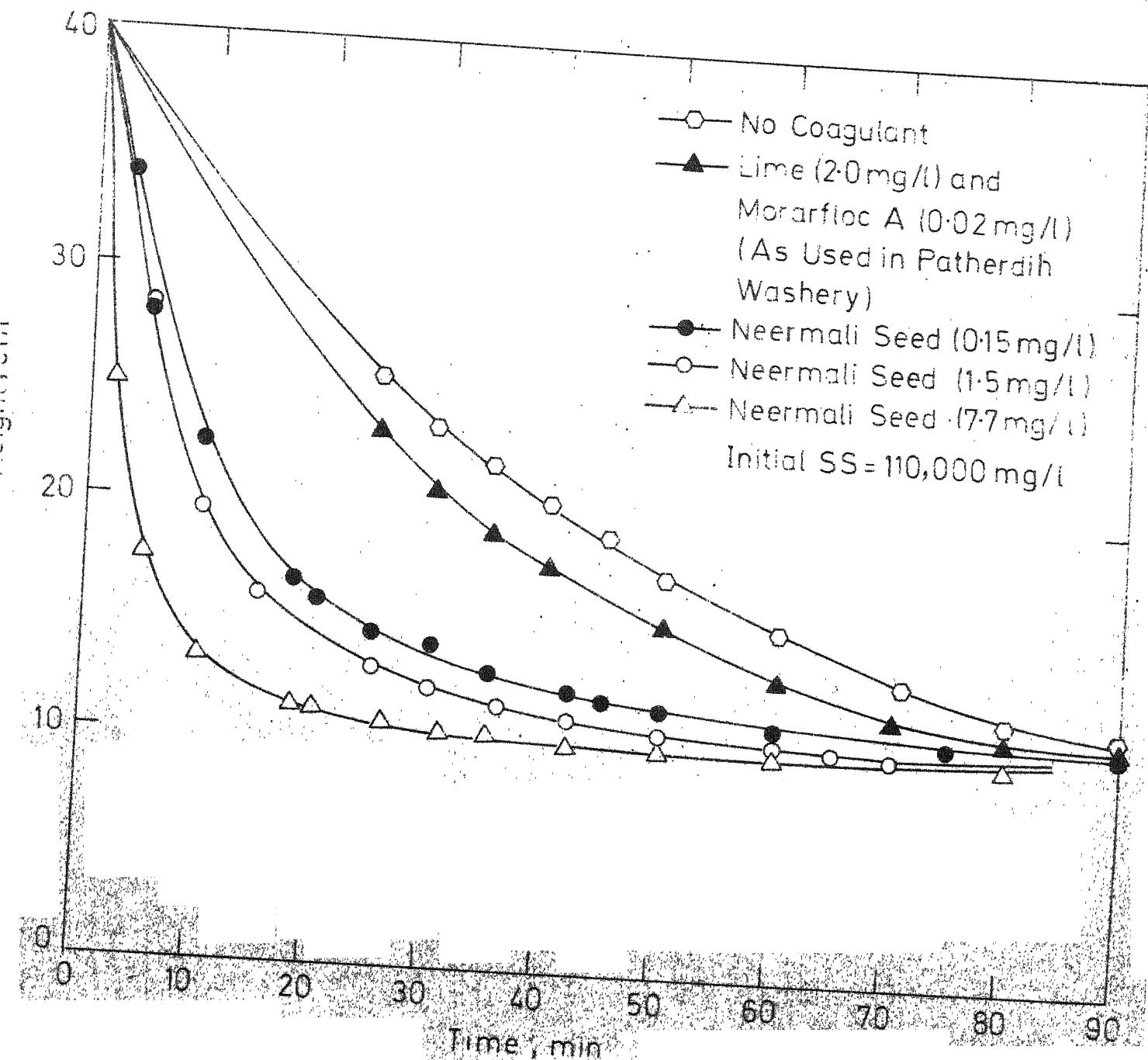
Fig.25 Interface Settling Curves of Thickener Feed with and without Various Coagulants
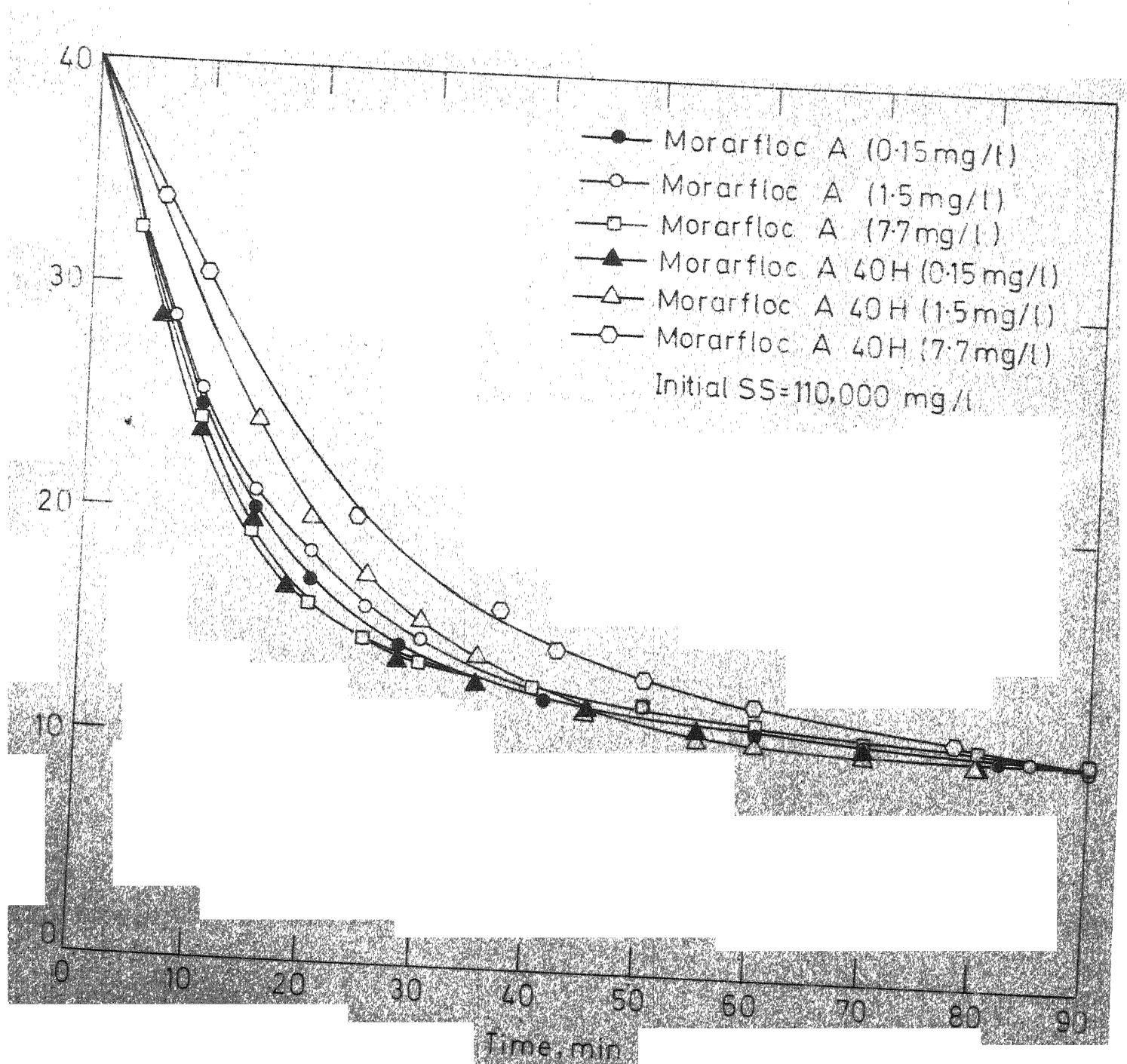
Fig 26 Interface Settling Curves of Thickener Feed with Morafloc as Coagulant

7. SUMMARY AND CONCLUSIONS

On the basis of the characterisation of effluent samples from several coal washeries it is shown that these effluents do not satisfy the specified limit of suspended solids concentration for discharge into inland surface waters. On the basis of laboratory settling studies of washery wastewater it is also apparent that the presently used method of coal washery wastewater treatment by settling ponds may not satisfy the discharge standard even when these ponds function with maximum theoretical efficiency. This indicates a need for further treatment of the effluent. It is demonstrated that inorganic coagulants with or without polyelectrolytes as coagulant aids, and polyelectrolytes as prime coagulants are effective in clarifying the effluent and producing good recovery of fine coals. Alternatively, the effluent or the wastewater (feed to the settling ponds) may be effectively treated by extended plain sedimentation. It is also shown that the efficiency of the thickener used in the closed circuit coal washing process may be improved by modifying the thickener operation as well as judicious coagulant addition.

Based on the findings of this investigation, using Patherdih coal washery as a model, the following conclusions may be drawn:

    (1) Inorganic coagulants like alum and ferric chloride as well as polyelectrolytes (ionic and nonionic) are effective as prime coagulants

in clarifying coal washery effluent. These
polyelectrolytes are also effective as
coagulant aids when used in combination with
alum or ferric chloride. Coagulation is
probably effected by destabilisation and charge
neutralisation.

(ii) Extended plain sedimentation is a feasible method
in treating coal washery wastewater and effluent
to produce a suspended solids concentration well
below the specified discharge standard.

(iii) It is possible to improve the efficiency of the
thickener used in the closed circuit coal washing
process by modifying the thickener operation as
well as coagulant addition.

8. SIGNIFICANCE OF THE STUDY AND SUGGESTIONS FOR FUTURE WORK

8.1. Significance of the Study

The present study is significant as it puts the problem of coal washery effluent treatment and disposal into proper perspective. Presumably, it is one of the very few studies so far undertaken in this area.

The most significant result of the study is the demonstration that chemical coagulation employing commonly used inorganic coagulants and polyelectrolytes is effective in reducing the suspended solids concentration of the effluent to an acceptable value and producing valuable recovery of good quality coal fines with a potential of inplant reuse of the treated effluent.

The extended plain sedimentation phase of the study is also significant because it shows how plain sedimentation with lower overflow rates may be effectively used for both coal washery wastewater as well as effluent treatment when sufficient land is available. This may be an attractive method for the Indian coal washeries since the presently used settling ponds may be suitably modified to function as extended plain sedimentation basins.

This study also indicates that the design and operation of the thickener used in the closed circuit coal washing process should be looked into carefully. It may be possible to improve the thickener underflow and reduce the

suspended solids concentration of the wastewater by modifying the thickener operation and/or judicial use of coagulants.

Finally, the results of this study suggest that the problem of coal washery wastewater/effluent treatment and disposal should be investigated in greater details so that some generalised recommendations may be made which would be beneficial for the present as well as the future coal washeries.

8.2. Suggestions for Future Work

On the basis of the results of the present study, it is felt that further investigations should be pursued in the following areas:

(i) Studies similar to the present one need to be undertaken using several other coal washeries so as to be able to make more generalised suggestions/recommendations for coal washery wastewater/effluent treatment keeping in view the recovery of coal fines as well as inplant reuse of the treated wastewater/effluent.

(ii) Investigation should also be undertaken to study the applicability of the methods employed in the present study to the treatment of effluent from the facilities provided for upgrading coal fines since the need for such facilities has been recognised (Sarkar, 1972).

REFERENCES

Addision, H., A Treatise of Applied Hydraulics, 4th ed., Asia Publishing House, Bombay, (1959).

Association of Environmental Engineering Professors, Environmental Engineering Unit Operations and Unit Processes Laboratory Manual, (July, 1972).

Banerjee, A.N., Chattopadhyay, J., Chakravarty, A.K., and Sarkar, G.G., "Properties of Some Coking Coal Slurries Obtained From Various Coal Fields," Jr. Min. Met. Fuels (Special Issue), 115 (1964).

Black, A.P., Birkner, F.B., and Morgan, J.J., "Destabilisation of Dilute Clay Suspensions With Labeled Polymers," Jr. Am. Water Wks. Asson., 57:1547 (1965).

Bulovtskii, V.S., and Pilyasov, F.L., "Polyacrylamide for Slurry Flocculation," Coke and Chemistry, 2:3 (1962).

Camp, T.R., "Sedimentation and Design of Settling Tanks," Trans. Am. Soc. Civil Engg., Paper 2285, III:895 (1946).

Chakravarty, A.K., Chattopadhyay, J., Sarkar, G.G., and Lahiri, A., "An Integrated Process (Oleoflotation) for Upgrading and Dewatering of Small Coal," Indian Patent No. 100675.

Chapman, D.L., Phil. Mag. 25:475 (1913).

Chattopadhyay, J., Chakravarty, A.K., and Sarkar, G.G., "Clarification of Washery Water by Flocculation," Jr. Min. Met. Fuels (Special Issue), 89 (1964).

Chattopadhyay, J., Chakravarty, A.K., Sarkar, G.G., and Lahiri, A., "A Study of Effectiveness of Various Flocculating Agents on Coal Washery Slurries," Jr.Min.Met.Fuel, 9:2:4 (1961).

Clark, J.W., Viessman, W., Jr. and Hammer, M.J., Water Supply and Pollution Control, 2nd.ed., International Textbook Co., Scranton, Pa., (1971).

Committee Report, "State of Art of Coagulation: Mechanism and Stoichiometry," Jr. Am. Water Wks. Asson., 63:63 (1971).

Das, N., Sinha, S.N., and Bhaskaran, T.R., "Survey of Pollution in Four Rivers in Bihar State," Proc. Symp. Water Pollution Control,CPHERI, Nagpur, 3:111 (1965).

Dhaneshwar, R.S., Personal Communication, (1976).

Eckenfelder, W.W.,Jr., and Melbinger, N., "Settling and Compaction Characteristics of Biological Sludges," Sew. Ind. Wastes, 29: 1114 (1957).

Eckenfelder, W.W.,Jr., and O'Connor, D.J., Biological Waste Treatment, Pergamon Press, New York, (1961).

Fitch, E.B., in: McCabe, J., and Eckenfelder, W.W.,Jr., (eds), Biological Treatment of Sewage and Industrial Waste - Vol. 2: Anaerobic Digestion and Solids-Liquid Separation, Reinhold Publishing Corp., New York, (1958).

Gieseke, E.W., "Flocculation and Filtration of Coal Flotation Concentrate and Tailing," Proc. 18th Industrial Waste Conference, Pardue University, Lafayette, Indiana, U.S.A., April 30, May 1 and 2 (1963).

Gillenwater, L.E., "Coal Washery Waste in West Virginia," Sew. Ind. Waste, 23 (1951).

Gouy, G., J. Phys., 4:9:357 (1910).

Harper, W.G., "Growing Use of Water in Coal Preparation Plants," Surveyor (Brit.), 119: 57 (1960).

Hummer, E.D., "Minus 48 Mesh Refuse Disposal at U.S. Steel's Gary Central Coal Preparation Plant," Mining Engineering, 17:3:63 (1965).

Indian Patent No. 100725 of 1965, Indian Council of Medical Research.

Indian Standard No.2490, Tolerance Limits For Industrial Effluents Discharged Into Inland Surface Waters, Part I - General Limits, (1974).

Kotkin, A.M., and Rozhnova, E.E., "Flotation of Slurries Coagulated With Polyacrylamide," Coke and Chemistry, 12:3 (1962).

Kumar, S., and Vishwanathan, K.K., "Damodar Becomes Industrial Sewer," The Indian Express, Dec.25 (1976).

LaMer, V.K., "Coagulation Symposium Introduction," Jr.Coll.Sci., 19:291 (1964).

LaMer, V.K., and Healy, T.W., "Adsorption-Flocculation Reactions of Macromolecules at Solid-Liquid Interface," Rev. Pure Appl. Chem., 13: 112 (1963).

Manual of Water Supply and Treatment, 2nd. ed., CPHERI,
    Ministry of Works and Housing, Govt. of India, 8? (1976).

Matijevic, E., Abramson, M.B., Ottewil, R.H., Schulz, K.F.,
    and Kerker, M., "Adsorption of Thorium Ions on Silver
    Iodide Sols," Jr.Phys.Chem., 65: 1724 (1961).

Matijevic, E., Janauer, G.E., and Kerker, M., "Reversal of
    Charge of Lyophobic Colloids by Hydrolized Metal Ions
    I. Aluminium Nitrate," Jr.Coll. Sci., 19:333 (1964).

McGarry, G.M., "Algal Flocculation with Aluminium Sulfate
    and Polyelectrolytes," Jr. Water Poll. Cont. Fed.,
    42:5 (1970).

Michaels, A.S., "Aggregation of Suspension by Polyelectrolytes,"
    Ind. Eng. Chem., 46: 1485 (1954).

Miller, L. B., "A Study of the Effects of Anions Upon the
    Properties of 'Alum floc', " Pub. Health Rep., 40:351
    (1924).

Noone, W.H., "Eliminating Stream Pollution From a Coal
    Preparation Plant," Mining Congress Jr., 49:8:27 (1963).

O'Melia, C.R., and Stumm, W., "Aggregation of Silica Dispersion
    by Iron (III)," Jr. Coll. Interface Sci., 23:437 (1967).

Packham,R.F., "Some Studies on the Coagulation of Dispersed
    Clays With Hydrolysing Salts," Jr. Coll. Sci., 20:81 (1965).

Pantulu, V.R., "Pollution of Rivers by Industrial Effluents
    and Its Effect on Fisheries," 2nd. Anniversary
    Commemoration Souvenir, Indian Asson. Water Poll.Control,
    Dec.: 100 (1965).

Posselt, H.S., Anderson, F. J., and Weber, W.J.,Jr., "Cation
    Sorption on Colloidal Hydrous Manganese Dioxide,"
    Environ. Sci. Tech., 2:12:1087 (1968).

Posselt, H.S., Reidies, A.H., and Weber, W.J.,Jr.,"Coagulation
    of Hydrous Manganese Dioxide," Jr. Am. Water Wks. Asson.,
    60:48 (1968).

Rao, M.N., and Sastry, C.A., "Treatment of Coal Washery Waste
    by Coagulation," Indian Jr. Environ. Health, 10:265 (1968).

Rich, L.G., Unit Operation of Sanitary Engineering, John Wiley
    and Sons, Inc., New York, N.Y. (1961).

Rozgaj, S., "Coagulation of Minutes in Coal Separation Waste Water," Khem. Ind. Zagreb (Jugoslav), 14:3:134 (1965), in: Chem. Abs., 64: 4783 (1966).

Ruehrwein, R.A., and Ward, D.W., "Mechanism of Clay Aggregation by Polyelectrolytes," Soil Sci., 73:485 (1952).

Sarkar, G.G., "Some Glimpses of the World-Wide Trends in Coal Preparation," Presented at the Indian School of Mines, Dhanbad on 20.4.77 in connection with the ISM Golden Jubilee Celebration.

Sarkar, G.G., Chakravarty, A.K., Bose, R.N., and Sinha, N.C., Studies on Coal Preparation in India, Central Fuel Research Institute, Dhanbad (1972).

Shubert, R.H., "Method for Treatment of Coal Washery Waters" U.S. Patent No.3,856,688, Official Gazette, 929:4:1698 (Dec. 1974).

Smith, G.N., "Lagoons in the Coal Mining Industry," Colliery Guardian, 216:471 (1968).

Sommerauer, A., Sussman, D.L., and Stumm, W., "The Role of Complex Formation in Flocculation of Negatively Charged Sols With Anionic Polyelectrolytes," Koll.-Z.Z.Polymere, 225:147 (1968).

Standard Methods for the Examination of Water and Wastewaters, 14th ed., Am.Pub. Health Asson., Inc., New York (1976).

Stern, O., Z. Electrochem., 30:508 (1924).

Streeter, V.L., Fluid Mechanics, 3rd. ed., McGraw-Hill Book Co., Inc., New York, N.Y. (1962).

Stumm, W., and Morgan, J.J., "Chemical Aspects of Coagulation," Jr. Am. Water Wks. Asson., 54: 971 (1962).

Stumm, W., and O'Melia, C.R., "Stoichiometry of Coagulation," Jr. Am. Water Wks. Asson., 60:514 (1968).

Talmadge, W.P., and Fitch, E.B., "Determining Thickener Unit Areas," Ind. Eng. Chem., 47:38 (1955).

Tamamushi, B., and Tamaki, K., "The Action of Long-Chain Cations on Negative Silver Iodide Sol," Koll.-Z.163:122 (1959).

Tripathy, P.N., Chaudhuri, M., and Bokil, S.D., "Nirmali Seed - A Naturally Occurring Coagulant," Indian Jr. Environ. Health, 18: 272 (1976).

Wax, N., ed., <u>Selected Papers on Noise and Stochastic Process</u>, Dover Publications, Inc., New York, N.Y. (1954).

Weber, W.J., Jr., <u>Physicochemical Processes for Water Quality Control</u>, Wiley Interscience, New York, (1972).

Yao, K.M., "Extended Plain Sedimentation," <u>Jr. Environ. Engg. Div. ASCE, 413: 101</u>, Proc. Paper 11392 (1975).

Zanoni, A.E., and Blomquist, M.W., "Column Settling Tests for Flocculant Suspensions," <u>Jr. Environ. Engg. Div. ASCE, 309: 101</u>, Proc. Paper 11356 (1975).